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In This Issue

The Detection of Modification in Animal Fibers
I. Use of the Ratio $\left(\frac{\text{Hookean Slope in } H_2O}{\text{Hookean Slope in Conditioned Air}}\right)$ — Harris M. Burte — 63

Some Relations of Fiber Properties to Fabric Hand
R. M. Hoffman and L. F. Beste — 66

Glycosidic Methoxyl Groups in Methanolyzed Cellulose
Richard E. Reeves, Laurence W. Mazzeno, Jr., and Carroll L. Hoffpauir — 78

Letters to the Editor
The Reaction Between Methanol and Hydrogen Chloride at 0° C
Richard E. Reeves, Carroll L. Hoffpauir, and Robert J. Demint — 81

Types and Dimensions of Fiber Scales from the Wool Types of Domestic Sheep and Wild Life
Gurbax Singh Mahal, Alexander Johnston, and Robert H. Burns — 83

Bikaner Wool, A Leading Carpet Wool, and Its Improvement
Gurbax Singh Mahal, Alexander Johnston, and Robert H. Burns — 94

INDUSTRIAL SECTION

Effect of Construction on the Laundering Shrinkage of Knitted Woolens
Herman Bogaty, Louis I. Weiner, Arnold M. Sookne, and Milton Harris — 102

The Technical Possibilities for a Regenerated Silk
Helmut Wakeham, R. K. Toner, H. R. Jolley, and H. S. Taylor — 110

Correlation Studies of Accelerated and Natural Weathering Tests of Protectively Finished Cotton Duck
P. J. Fynn, Catherine N. Daly, Constance M. Fleming, and J. D. Dean — 116

Book Reviews — 123

Editor: Julian S. Jacobs *Production Editor:* Lois E. Emma

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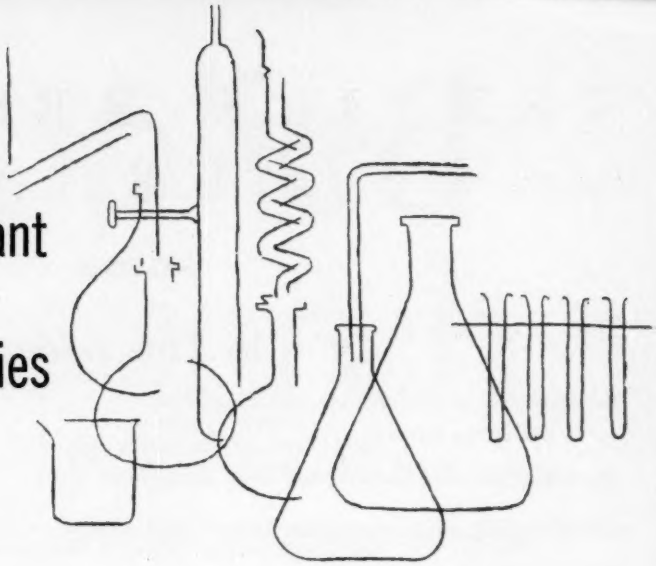

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TEXTILE RESEARCH JOURNAL

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The Detection of Modification in Animal Fibers*

I. Use of the Ratio $\left(\frac{\text{Hookean Slope in } H_2O}{\text{Hookean Slope in Conditioned Air}}\right)$

Harris M. Burte

Contribution of Textile Research Institute and The Department of Chemical Engineering, Princeton University, Princeton, N. J.

Abstract

The ratio $\left(\frac{\text{Hookean slope in } H_2O}{\text{Hookean slope at 65\% R.H.}}\right)$, where both measurements of the Hookean slope are on the same fiber, is shown to be independent of fiber cross-sectional area, and, for a given fiber type and previous history, the fiber-to-fiber variation of the ratio is small. Since chemical treatments markedly affect this ratio, its use to detect chemical process modification of animal fibers presents attractive possibilities.

THE PROCESSING of wool involves imposition of a wide variety of severe physical and chemical conditions upon the fibers. In order to control the various phases of processing and develop improvements in the processes, it is necessary to have reliable methods of measuring changes taking place in the fibers. While considerable information of this type can be obtained from yarn and fabric tests, it is often desirable to measure the mechanical properties of single fibers, thus eliminating the complications of yarn and fabric geometry. This work was aimed at developing a single-fiber test capable of yielding results with a minimum dependence upon fiber-to-fiber variation in effective cross-sectional area.

* Sponsored by The Wool Bureau, Inc., acting for the American Wool Council and the International Wool Secretariat; the Office of Naval Research, Navy Department; and a number of wool manufacturers. Other aspects of this work are sponsored by the Bureau of Agricultural and Industrial Chemistry of the U. S. Department of Agriculture.

The average cross-sectional areas of wool fibers vary greatly from fiber to fiber, even for fibers growing in close proximity on the fleece. Consequently, the parameters of mechanical behavior, when measured in force units, have a very high fiber-to-fiber variance, and it is desirable to reduce them to stress units by dividing by an average cross-sectional area or an average linear density. (Cross-sectional area as used in this work is a size parameter indicating that one fiber has more fiber material in a cross section perpendicular to the load than another fiber. It might be thought of as the cross-sectional area of a bone-dry fiber.) The auxiliary measurement of the cross-sectional area is frequently laborious and not very accurate, especially for wool fibers which are nonuniform along their length. Therefore, the variance of the mechanical parameters, even when expressed in stress units, is often quite high, necessitating determinations on a large number of samples in order to detect small differences between groups of fibers. The present communication describes a *low variance* index of mechanical properties which can be used to detect chemical process modification, and which eliminates the need for cross-sectional area or linear density measurements.

A typical force-extension curve, for a wool fiber, in the low range of extension is shown in Figure 1. In the region OA the crimp in the wool fiber is being removed as the fiber extends; in the region AB (the Hooke's law region) the force is linear with extension; in the region BC the Hookean region is passed and the slope of the curve starts to decrease. The slope of the curve in the region AB is the Hookean slope (k). It has recently been shown [1] that nondestructive measurements of the Hookean slope can be achieved with quite small time intervals between successive measurements. The Hookean slope, therefore, can be *nondestructively* measured on a fiber at 65% R.H. (k_{65}), and shortly thereafter can be measured on the *same* fiber in water (k_{H_2O}). Both k_{65} and k_{H_2O} are parameters of mechanical behavior (in force units) measured over the same low range of extension, and should be dependent upon the same cross-sectional area of the fiber. The ratio (k_{H_2O}/k_{65}) should be independent of the cross-sectional area of the bone-dry fiber, and a plot of k_{H_2O} *vs.* k_{65} for a series of fibers differing only in cross-sectional area should be a straight line passing through the origin. This relation is closely approximated by the data plotted in Figure 2 for 44 Columbia 56's wool fibers. For these fibers, the mean value of (k_{H_2O}/k_{65}) was 0.462, and the coefficient of variation was only 5.35%. The small variance is due to errors in measuring the Hookean slope and to differences between fibers not related to fiber size.

It has long been known [2, 4, 5, 7, 8] that chemical treatment will cause a much greater change in the wet-state mechanical properties of the fiber than in the dry-state mechanical properties. The quantity k_{H_2O} will, therefore, be much more affected

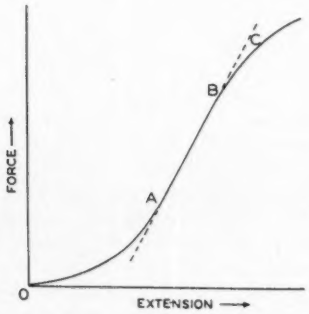

FIG. 1. *A typical force-extension curve for a wool fiber. Low extension range.*

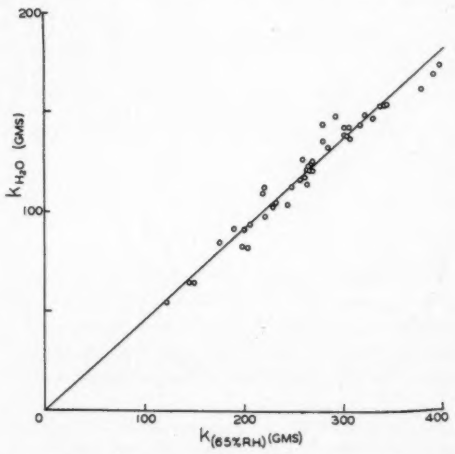

FIG. 2. *Plot of the Hookean slope in water* (k_{H_2O}) vs. *the Hookean slope at 65% R.H.* (k_{65}) *for 44 Columbia 56's wool fibers.*

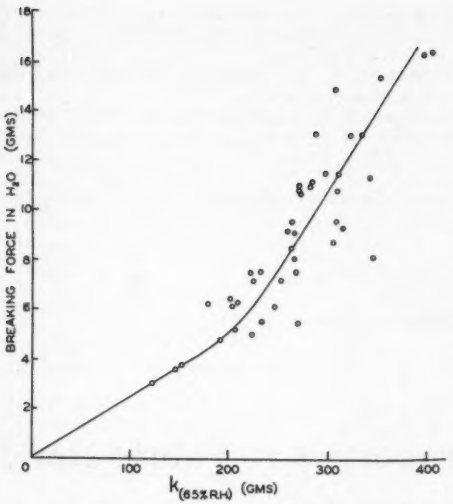

FIG. 3. *Plot of the breaking force in water* vs. *the Hookean slope at 65% R.H.* (k_{65}) *for 43 Columbia 56's wool fibers.*

by chemical treatment than k_{65},* and the ratio (k_{H_2O}/k_{65}) is an index, sensitive to chemical modification of the fiber, which has a low fiber-to-fiber variance. It is reasonable to assume that purely physical modification, such as that producing a flaw or a crack in the fiber, will affect k_{H_2O} and k_{65} equally, and will not, therefore, affect the ratio (k_{H_2O}/k_{65}).

Experimental

An Instron tensile tester [3] located in a conditioned room at 65% R.H. and 70°F was used. The experimental technique now employed is measurement of k_{65} by extending the fibers very slightly beyond *B* (Figure 1) and immediately contracting [1]. After contracting, the fiber is allowed to stand for 10 to 15 min.; then it is immersed in water for 5 min. and k_{H_2O} is measured. These time intervals are probably conservative, and future work may show that they can be appreciably reduced without affecting the results. Tables I and II, respectively, show how the technique was applied to detect chemical modification due to boiling in distilled water and due to treatment with cold sodium bisulphite. In each case, fibers were randomly selected from the samples of treated and untreated wool. It is possible to show statistically significant differences with a small number of samples.

* k_{65} is used here because the conditioned room available was at 65% R.H. A lower relative humidity for the dry Hookean slope might give a more sensitive test.

TABLE I. COLUMBIA WOOL 58's–60's
(TREATMENT: BOILING IN DISTILLED H_2O FOR 1 HR.)

	Untreated	Treated
Number of samples	10	10
Average (k_{H_2O}/k_{65})	0.468	0.402
Standard deviation	0.0323	0.0258
Coefficient of variation	6.9%	6.4%

Student t [6] = 4.97**, indicating a significant difference between the means of the treated and the untreated samples.

TABLE II. COTSWOLD WOOL
(TREATMENT: IMMERSION IN 11% $NaHSO_3$ (BY WEIGHT) SOLUTION AT 20° C FOR THE SPECIFIED TIME AND THEN WASHING WITH DISTILLED WATER FOR 24 HRS.)

	Time of treatment:			
	Untreated	10 min.	24 hrs.	114 hrs.
Number of samples	11	11	11	11
Average (k_{H_2O}/k_{65})	0.485	0.480	0.452	0.428
Standard deviation	0.0412	0.0255	0.0391	0.0383

From analysis of variance, the Snedecor [6] ratio, F = 5.705** (3, 40 d.f.), indicating a significant effect due to time of treatment.

Since the measurements of k_{65} and k_{H_2O} are nondestructive (*i.e.*, have no measurable effect on the fiber properties), it is possible to continue the test and measure other parameters of the mechanical behavior of the wet fiber. An obvious extension of the method described above would be to reduce the variance of all parameters measured in force units by dividing by k_{65}. This may lead to erroneous results, however, especially for nonuniform fibers. For example, the cross-sectional area which modulates the force at break may not bear a linear relation to that which modulates k_{65}. Thus, for the same fibers used to obtain the data of Figure 2, a plot of the breaking force in water *vs.* k_{65} gives a curvilinear relation (Figure 3) and a simple division of the force at break by k_{65} is not permissible.

Acknowledgment

The author wishes to express his appreciation to Professor J. C. Whitwell, under whose direction this work was done, and to Dr. J. H. Dillon for

reading the manuscript and helping to clarify the presentation.

Literature Cited

1. Burte, H. M., *J. Applied Phys.* **21**, 494–9 (1950).
2. Harris, M., and Brown, A. E., TEXTILE RESEARCH JOURNAL **17**, 323–9 (1947).
3. Hindman, H., and Burr, G. S., *Trans. Am. Soc. Mech. Eng.* **71**, 789–96 (1949).
4. Krais, P., *J. Text. Inst.* **23**, P144–6 (1932).
5. Russina, *Melliand Textilber.* **12**, 404–6 (1931); **13**, 207–9 (1932).
6. Snedecor, G. W., "Statistical Methods," The Iowa State College Press, 1946.
7. Viertel, O., *Melliand Textilber.* **17**, 868–72 (1936).
8. Woods, H. J., *Proc. Leeds Phil. & Lit. Soc. (Sci.)* **3**, 577–83 (1940).

(*Manuscript received November 3, 1950.*)

Some Relations of Fiber Properties to Fabric Hand*

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THE CONSUMER has but little direct interest in fiber properties; it is mainly *fabric quality* which establishes his opinion of various fibers. The textile scientist, on the other hand, finds it necessary to understand the contribution of fiber properties to fabric quality; the work reported in this paper has been directed toward this objective.

More particularly, the somewhat intangible thing called the "handle" or "hand" of fabrics is discussed herein. By this is meant the impressions which arise when fabrics are touched, squeezed, rubbed, or otherwise handled. The handling of a fabric may convey visual impressions as well as tactile ones; therefore, it seems proper to include in the properties considered covering power and luster, although no experimental work has been done on these two properties in this laboratory.

The human hand is a sensitive instrument, capable of detecting small differences in fabric quality. The results of hand tests are expressed in such words as: soft, crisp, firm, hard, harsh, boardy, dead, lively, wiry, cold, warm, waxy, dry, muss-resistant, etc. These descriptive terms are useful; however, a more quantitative and reproducible scale of evaluation is desirable. The ideal procedure would be to correlate these fabric characteristics with physical terms which can be precisely measured. There is abundant literature on fiber testing and a lesser amount on fabric tests, but there is relatively little on the interpretation and correlation of instrument testing results with the human evaluation of fabric hand.

The material presented in this paper is based in part on the literature and in part on the data and experience of this and other Du Pont laboratories. Several concepts which should be regarded at this time as largely speculative have been included with the hope that they may be helpful or suggestive of further work.

FIG. 1. *Hanging-heart test.*

* Presented at the Gordon Research Conference on Textiles, July 22, 1949. Presented in part at the Annual Meeting of Textile Research Institute, New York City, December 1, 1949.

TABLE I. FIBER STIFFNESS

	Initial modulus of elasticity (M_i)	Denier (d)	Bending stiffness ($M_i d^2$)
High stiffness ⟶ firm fabrics			
Carpet wool	35	10	3,500
Linen	208	2.3	1,100
Medium stiffness ⟶ crisp fabrics			
Suiting wool	20	5	500
Cellulose acetate	45	3	400
Low stiffness ⟶ soft fabrics			
Angora rabbit fur	40	2	160
Cellulose acetate	45	1.5	90
Silk	90	1	90
Rubber monofil	.04	50	100

Those descriptive terms which relate to a certain basic fabric property—stiffness, for example—have been grouped together, and the contribution of the underlying fiber property has been indicated. The geometrical or mechanical effects of fabric and yarn construction [1, 7, 15, 20, 21, 29] are equally important variables, but these belong to an essentially different field of investigation from that covered in this paper; they cannot, however, be entirely overlooked in the present discussion.

The fabric properties are taken up in the following order: stiffness, compliance, liveliness, weight, leanness and bulk, compressibility and thickness, waxiness, friction, contact warmth, drape, smoothness and luster, covering power, and contour retention and resilience.

Fabric Stiffness

The stiffness of a fabric is an important factor in that composite characteristic called "hand." A simple and direct measure of stiffness, or "flexural rigidity," is the *bending moment per unit curvature.* This quantity can be determined for a fabric by means of the "hanging-heart" test discussed by Peirce [19]. The apparatus is illustrated in Figure 1. A fixed length of fabric 1 cm. wide is used; the flexural rigidity, G, is computed from the distance the loop hangs down and the weight per sq. cm. of the fabric.

TABLE II. FABRIC STIFFNESS

Firm fabrics	Crisp fabrics	Soft fabrics
High $M_i d^2$	Medium $M_i d^2$	Low $M_i d^2$
High twist		Low twist
Round filaments		Flat filaments
Plain weave		Satin weave

The three basic fiber properties that have the most to do with fabric stiffness are the elastic modulus, the lateral dimensions, and the cross-sectional shape.* The bending stiffness of a circular rod is proportional to the modulus of elasticity multiplied by the fourth power of the radius. For a single fiber this becomes the square of the denier times the modulus, provided the density is neglected for the moment.

Denier and modulus data for fibers which lead to three recognizably different degrees of fabric stiffness by hand tests are shown in Table I. The two extremes of fabric stiffness are denoted by the words "firm" and "soft." The word "crisp" has been chosen to describe the stiffness of fabrics falling in the intermediate range. The "initial modulus," M_i, represents the initial slope of the stress-strain curve and has the dimensions of g. per den. per 100% elongation†; d denotes denier. Linen is a stiff fabric because of its high modulus. Carpet wool is stiff because of its high denier. Angora rabbit fur is extremely soft because of its low denier. For the crisp hand of a men's suiting fabric, a denier of 5 with a modulus of 20 is about right. A 50-den. monofil of rubber would be a soft filament because of its extremely low modulus.

$M_i d^2$ is a reliable criterion of relative fabric stiffness only so long as the other variables remain constant. When this condition is not met, it is necessary to take into account additional modifying influences, such as are shown in Table II. The

* Mathematical equations relating these three quantities can be found in any standard textbook on the strength of materials. The application of these equations to textile fibers is discussed by Harold DeWitt Smith [28].

† An isotropic body has only one Young's modulus, which may be measured either by bending the specimen or by stretching it. Since textile fibers are not isotropic, the value obtained for the Young's modulus will, in general, differ with the direction of measurement. All modulus data given in this paper refer to the tensile modulus, although these data are used in the present study, as in Table I, to predict relative flexural stiffness to a first approximation. Data obtained in this laboratory [3] indicate that the approximation is probably good to ±20% in the case of synthetics. The fact that the time dependence of the modulus is ignored affects the comparisons of Table I to a still smaller degree.

shape of the filaments, the amount of twist in the yarn, interfiber friction, and the type of weave affect the stiffness. A satin weave is softer than a plain weave, for example, because the warp threads are not locked in by alternate picks, but only by every fifth pick or every ninth pick. It would be outside the scope of this discussion to go any further into the contributions of fabric geometry to stiffness.

Compliance

The stress-strain curves for silk and wool fibers have different shapes, as shown in Figure 2. The significance of this difference in shape as regards fabric hand has been less evident, perhaps, because of an all-too-common preoccupation with tenacity and elongation.

Furthermore, there are many ways in which one stress-strain curve may differ from another in shape. The problem has been to locate the significant aspects of the total curve. The shape of the curve, for example, governs the area under it. This area has been associated with the toughness of the material, whether the material be a steel member in an engine or a textile fiber in a fabric. As mentioned in the preceding section, the initial modulus represents one aspect of how the course of the curve affects fabric hand.

However, the present authors believe that, in the case of fabric hand, the significance of the curve persists out to the range between 5% and 10% elongation. The compliance ratio was developed [3, 14] for the purpose of characterizing the change in stiffness (or its reciprocal—compliance) in that region of extension or strain.

When the silkworm spins a fiber, he stretches it and orients the molecules along the fiber axis.

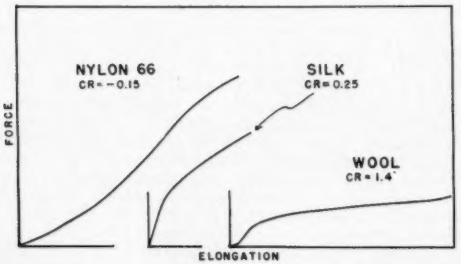

FIG. 2. *Relationship of compliance ratio to shape of force-elongation curve.*

TABLE III. STIFFNESS AND COMPLIANCE

Fabrics	Stiffness	Compliance	Description
Knitted wool	Low	High	Soft and compliant
Woolens	Medium	High	Crisp but compliant
Gabardines	High	High	Firm but compliant
Silk satins	Low	Low	Soft and limp
Silk taffetas	Medium	Low	Crisp and somewhat harsh
Linens	High	Low	Firm and harsh

Orientation is similarly obtained in making Cordura rayon. This orientation gives both silk and Cordura stress-strain curves which begin as straight lines and curve downward only moderately at higher elongations. The compliance ratio, which measures this downward curvature, is 0.15 for Cordura and 0.25 for silk.

In the wool fiber, the chains are not pulled out straight, but are folded. When the fiber is elongated about 2%, these folded molecules begin to open up, and, as a result, the stress-strain curve for wool dips down sharply. The compliance ratio for a typical wool is 1.4, which is more than 5 times the value for silk.

Because of its extremely high orientation, nylon has a stress-strain curve that soon begins to curve upward, resulting in a negative compliance ratio, −0.15.

That the hand can detect such differences has been demonstrated in this laboratory by constructing two mechanical devices with levers and springs.

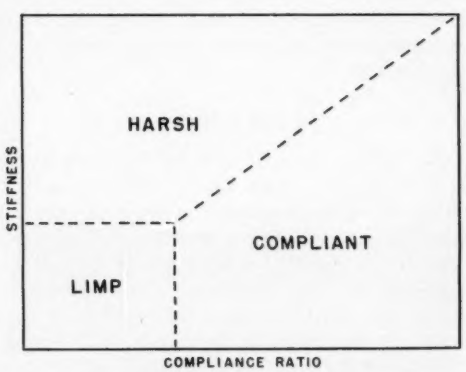

FIG. 3. *Dependence of fabric hand on compliance ratio and stiffness.*

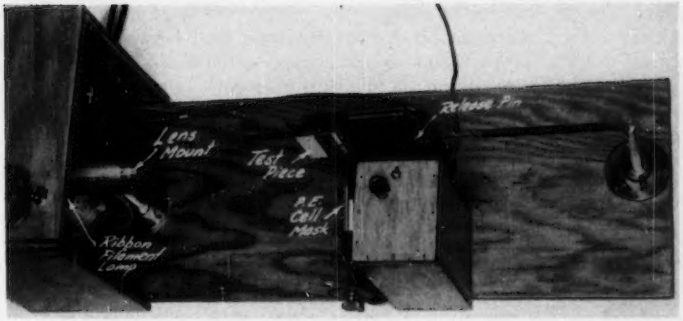

FIG. 4. *Fabric liveliness tester*

The stress-strain curve bends downward in one case and upward in the other, and the hand can detect this difference in behavior by squeezing the implements. These same differences can also be detected by comparing the hand of a wool gabardine and of a cotton twill of comparable weight. Therefore, as shown in Figure 3, both the initial stiffness and the compliance ratio explain the harsh-compliant-limp aspect of fabric hand.

As used in this work, the *compliance* of a fabric is not exactly the opposite of the stiffness. Stiffness refers to the initial modulus. Compliance describes the diminishing modulus at higher deformations. We propose, therefore, to associate the word "compliant" with the phrase "to yield."

Harsh means unyielding. It refers not to the initial behavior, but to the failure to show a diminishing rate of resistance build-up at higher deformations. Harshness is not the opposite of softness; it is the opposite of compliance. These definitions are perhaps arbitrary, but they make it possible to describe adequately the complex characters of such materials as those listed in Table III.

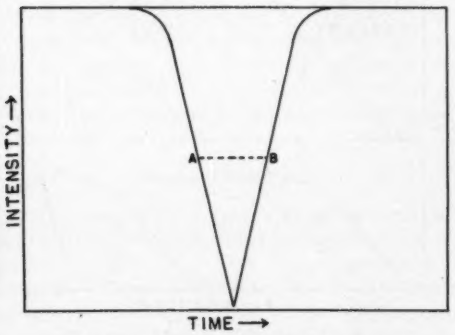

FIG. 5. *Liveliness test: recorder trace.*

In an earlier paper [3] it was shown that a great many fibers are characterized by a compliance ratio of about zero. Not a single one of these fibers would be satisfactory in a worsted type of suiting. On the other hand, the wool-like fibers are characterized by a fairly low modulus and a high compliance ratio. In between are a number of general-purpose fibers, such as viscose and acetate rayons.

Liveliness

The liveliness of a silk handkerchief is a property known to all stage magicians, and it has been put to work in many spectacular magic tricks. In woolen and worsted goods, the value of this property is best accounted for by the realization that it is something we would miss if it were absent. In its absence, we have a "dead" fabric.

A liveliness test instrument developed in this laboratory by Dr. J. W. Ballou is shown in Figure 4. At the left is a light source; to the right of this is a photoelectric cell. After release, the fabric interrupts the light to the cell momentarily. This light intensity curve is recorded on a Brush direct-inking oscillograph having a full-scale response time of 0.008 sec. The type of record obtained is illustrated in Figure 5. The average rate of opening between the two half-maximum points (*A*, *B* in Figure 5) has been used as a tentative measure of liveliness. This test reveals that the liveliest fabrics can open from a 180° fold in a time as short as .02 sec.

It was postulated that with a given polymer, weight, thickness, and weave, the rate of opening

might be an acceleration effect—that is, proportional to the force operating to open the fabric, or, more exactly, proportional to some exponential power of the force. From the physical laws governing rotary motion, it is known that the angle θ traversed in time t is proportional to the accelerating torque, T, divided by the moment of inertia, I, as follows:

$$\theta = \frac{1}{2}\frac{T}{I}t^2.$$

Taking T as a function both of G (the fabric stiffness) and of θ (since the operating torque will decrease as the test sample swings open), then $T \sim G/\theta$. It follows, therefore, that $\theta^2 \sim \frac{1}{2}Gt^2$, and that the velocity $\frac{\theta}{t}$ (or liveliness) is proportional to $\sqrt{G}$.

This prediction was borne out, as shown in Figure 6, which is a plot of liveliness against the square root of G, the flexural rigidity. These results apply to a series of polyethylene terephthalate fabrics. G was varied by changing the filament denier while keeping the yarn count, weave, and weight constant. A small variation in thickness was observed in the fabrics, but the scatter of points shows no correlation with this variable. The filled circle applies to a wool of the same construction.

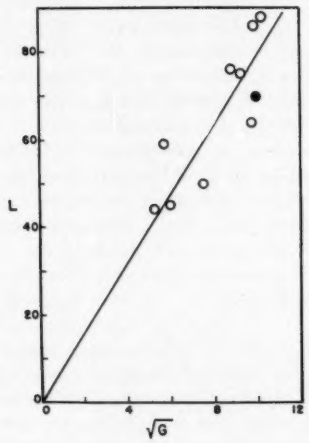

FIG. 6. *Fabric liveliness* vs. *square root of stiffness. Open circles—polyethylene terephthalate. Filled circle—wool.* L—*liveliness in cm./sec.* G—*flexural rigidity in mg. cm.*

Figure 6 indicates that there is a correlation between liveliness and the square root of the stiffness. Accordingly, we propose to divide the rate of opening by $\sqrt{G}$ in order to obtain the "intrinsic liveliness" of a material. Probably different polymers show different intrinsic livelinesses—that is, in a graph of liveliness *vs.* stiffness, the points for acetate rayon will probably fall on a line which is different from the line for polyethylene terephthalate; viscose rayon will have its own line, etc.

There is a rather different aspect of liveliness, which is appreciated when a fabric is wadded up in the hand and squeezed several times. This aspect of liveliness is concerned solely with the sense of touch and is sometimes referred to as "springiness." While it is true that fabrics which open most rapidly in a machine test usually feel the springiest, the correlation is not perfect. Also, the time scale involved in squeezing a fabric in the hand is of the order of seconds or tenths of a second instead of the hundredths of a second required for a fabric to flop open on the machine.

It may be that what is really felt in a hand test for springiness is the *recovery modulus*, or slope of the hysteresis loop on the return cycle. In Figure 7, we note that the recovery of sample *B* in the time allowed is poor; the recovery modulus is higher than the initial modulus, which means that the force with which the fabric presses against the hand drops off quite rapidly. A material with this type of curve would be called "leathery," "dead," or "mushy," depending upon whether the stiffness

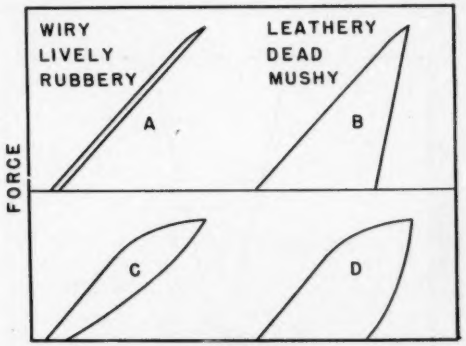

FIG. 7. *Relationship of springiness to fiber hysteresis loop.*

were high, medium, or low. Sample *A*, on the other hand, has a hysteresis loop typical of metals, silk, or rubber. It would be called "wiry," "lively," or "rubbery," depending upon the stiffness. (The elongations considered here are of the order of 1% or 2%.)

The shape of the first half of the loop is not important here. For example, note sample *D*, which resembles viscose rayon, and sample *C*, which resembles wool. Since curves of these two types usually accompany intermediate moduli, the appropriate adjectives here are "dead" and "lively," respectively.

It would be tempting to ascribe this entire effect to the recovery characteristics of the individual fibers, but this would not be quite accurate. Certainly, interfiber friction must play a role.

In summary, the liveliest fabrics open from a 180° fold in a very short time interval, while fabrics characterized as "dead" by hand tests may require over 5 times as long. The varying liveliness felt when one *handles* various fabrics may depend somewhat upon stiffness, but probably is even more dependent upon the shape of the hysteresis loop, upon interfiber friction, and perhaps also upon other properties that are not as well understood.

Weight

Another factor that can affect the hand and the apparent stiffness of a fabric is its weight per sq. yd. This sometimes colors one's judgment of the properties of one fiber *vs.* another in fabric tests. The obvious solution would be to make all laboratory test fabrics the same weave count and to use the same denier yarn. However, this cannot always be done because of shrinkage. Furthermore, not all yarns have the same density; therefore, they can vary in diameter even though the denier is the same. This influences the maximum number of picks per inch that can be pounded into a fabric on the loom.

Leanness and Bulk

One characteristic of a piece of ordinary cheesecloth is its light weight, and another is its leanness; but a heavy fabric, such as burlap, can also be lean or sleazy. Figure 8 illustrates one of the factors involved in the leanness of a fabric. When yarn diameter is equal to the distance between yarn centers, the "coverage," D/P, is complete ($D/P = 1$) and the fabric has minimum leanness. The factor D/P is proportional to the "cover factor" employed by Peirce [20] as long as yarns of equal bulk density are involved. "Coverage," as distinct from visual covering power, is only one of the factors involved in leanness. For example, in a knitted structure a much lower coverage would be tolerated before the term "lean" would apply than is the case with flat fabrics. Evidently, then, the yarn density and type of construction also enter the picture. In addition, a fabric which is not lean may be either lofty or hard, depending upon the apparent yarn density. Also, the property of compressibility probably favors an impression of loft. Table IV summarizes these relationships.

TABLE IV. LEANNESS

Lean	*Lofty*
	High or medium coverage Low-apparent-density yarn
Low coverage	*Hard*
High- or low-apparent-density yarn	High coverage High-apparent-density yarn

The term "coverage," as used here, is merely a matter of fabric geometry; apparent yarn density must be explained in terms of simpler factors.

Low yarn density is primarily due to low twist and intense crimp in the filaments, to the fiber elastic properties, and, to a lesser degree, to low polymer density.

Raising a nap or fuzz on the surface of a fabric is another way of obtaining bulkiness; this is one difference resulting from the use of staple yarns instead of continuous yarns. However, the really significant difference is a more hidden effect which, we believe, has to do with crimp retention. This effect is indicated in Figure 9. If we crimp a con-

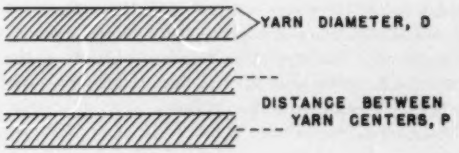

FIG. 8. *Definition of fabric coverage.*

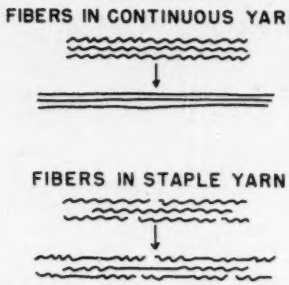

FIG. 9. *Retention of bulk in staple yarns under tension: suggested mechanism.*

tinuous yarn and then pull the two ends, the yarn would straighten out and the crimp would be removed. However, the individual fibers in a staple yarn are held together by friction and twist. When a staple yarn is elongated, the individual fibers are not under a uniform tension throughout their lengths. Near the ends of the fibers the tension may be quite low, and the crimp stays in. Therefore, the advantage of cutting up continuous yarn into staple may be partly the retention of crimp in order to obtain bulkiness. Certainly, it is not cut for the sole purpose of providing a fuzz or nap on the cloth, because this is sometimes objectionable and is removed by either a shearing or singeing process.

Under certain conditions, the presence of crimp in a fiber before weaving may not be particularly important in the final fabric. The act of weaving is a crimping process itself. Many fabric experts refer to crimp as the wave form taken by a thread as it passes alternately over and under other threads. For the most effective results, the fiber crimp must be finer than the fabric crimp, or it will be overwhelmed and will contribute little to yarn bulkiness. A crimp of 12 to 14 crimps per in., such as is commonly found in rayon staple, can no longer be found by microscopic studies in fabrics the pick counts of which are as high as 40 or 50 picks per in. (Figure 10). On the other hand, a portion of the natural crimp in wool is this fine and contributes to the bulkiness of the final fabric.

Another factor in yarn density has been proposed by Cassie [6]. This quantity, the "tightness factor," depends upon the torsional and flexural elastic constants of the separate filaments. To explain it briefly, a filament in a twisted yarn forms a helical

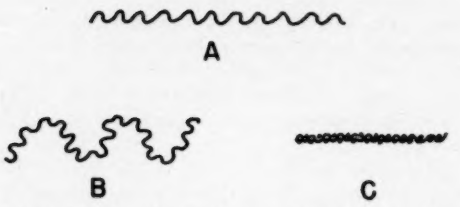

FIG. 10. *Relative effectiveness of fiber crimp.* A—*Fiber with 20 crimps/in.* B—*Crimp effective in knit fabric or flat fabric of low pick count.* C—*Crimp less effective in fabric of high pick count, such as 40 picks/in.*

spring. When such a spring is stretched, it tends to become smaller in diameter by the process of torsion and larger in diameter by the process of bending. A pair of metal springs can be constructed to illustrate this phenomenon (Figure 11). Both springs are wound from the same flat strip of metal, but the orientation in the right-hand spring is such as to make it difficult for it to bend. Accordingly, it elongates chiefly by torsion, with a consequent tightening up, as shown by the pointer (right photograph). Bending is easy for the other spring; as a consequence, it tends toward a larger diameter as it elongates. Table V gives tightness factors (all reduced to the same cross-sectional area) for a number of commercial yarns. A negative value goes with the effect of becoming more open on stretching.

The formula for tightness factor is:

$$TF = \left(\frac{1}{GK} - \frac{1}{EI}\right)\frac{\text{Area}^2}{2\pi},$$

where TF = tightness factor; G = torsional modulus; K = torsional moment of inertia; E = Young's modulus; I = moment of inertia about the neutral plane.

Compressibility and Thickness

Compressibility exerts an influence on a scale of fabric values ranging from hard to lofty. This property is probably a combination of yarn and

TABLE V. TIGHTNESS FACTORS

66 Nylon	2.2×10^{-10} cm.^{3}/dyne
Cordura tire-cord rayon	.7
Acele acetate rayon	.5
Viscose rayon	.1
Wool 64's grade	−.1
Casein fiber	−.2

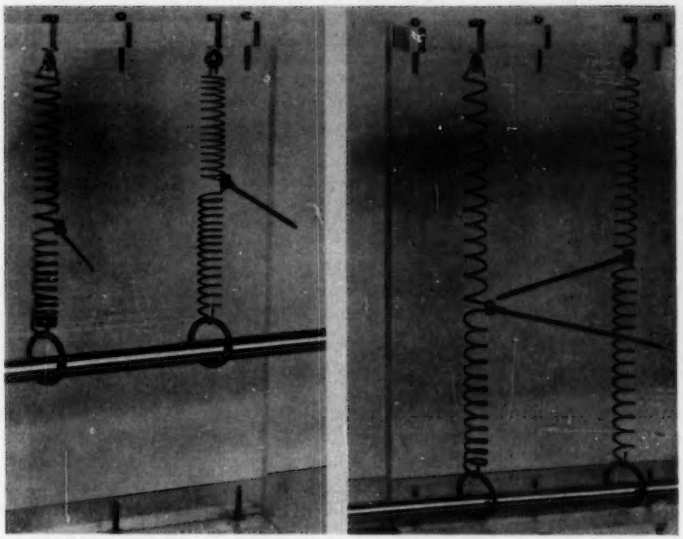

FIG. 11. *Device to illustrate the operation of the tightness factor.*

fabric density and the flexural stiffness of the fibers. An excellent system for measuring compressibility has been devised by Schiefer [26, 27]. The Schiefer instrument could be improved by substitution of electronic devices for some of the mechanical elements. Studies of the compressibility of random masses of fibers (rather than fabrics) have been published by Rees [25] and by Finch [11].

Thickness is a property which is readily sensed in a hand test. Furthermore, it influences our judgment of more complex tactile properties which depend upon compressibility and resistance to bending. Therefore, in order to separate bending-resistance into its fundamental components, one must first know the thickness. Unfortunately, the thickness of a fabric is not easy to measure. Because of its compressible nature, and especially because of the nap or fuzz which may be present on its surface, a fabric has no well-defined boundaries.

For these reasons, thickness is often measured over a range of pressures. The results have been said to follow the formula of Peirce:

$$t_w = t_o e^{-xw},$$

where t_w = thickness under pressure w, t_o = thickness under no pressure, and x is a constant to be determined. This equation offers a mathematical means of obtaining t_o by extrapolation to zero pressure. On the other hand, data obtained on an electronic compressometer indicated that the Peirce formula was not obeyed very well at the low pressures—*i.e.*, in the critical region for extrapolation. In the case of wool, polyethylene terephthalate, and Orlon acrylic fiber, our data were better fitted by the following formula:

$$w = k(t_o - t_w)^a$$

In each instance the exponent a showed the curious feature of increasing suddenly from a value of about $\frac{3}{4}$ at low pressures to a value of about 3 at medium and high pressures. This behavior probably reflects a fundamental change in the compression process. Perhaps the process changes from a bending of superficial hairs to a real compression of the fabric. If further work indicates this hypothesis to be true, then the thickness at which the exponent changes might well be taken as a meaningful fabric parameter. In conclusion, the standard load of 1 lb. per sq. in. for thickness measurements seems to be much too high where the effect of thickness on the hand is in question. This seems especially true for bulky, easily-compressible fabrics.

Waxiness

Polyethylene has often been classified as somewhat greasy or waxy in comparison with wool, for

TABLE VI. WAXINESS INDEX

Material	Waxiness index (1,000 (M_i/G^2))*
Polyethylene	790
66 Nylon	250
Polyethylene terephthalate staple	64
Orlon acrylic staple	39
Silk	28
Wool	21
Viscose rayon	18
Acele acetate rayon	14

* The unit for both M_i and G is g./den. G was measured in each instance on single filaments by means of a torsion pendulum. The factor 1,000 is used to obviate the need for decimals.

example, which is said to have a "dry" hand. Some samples of the same polymer are waxier than others, and this poses an interesting question as to why they are. Dr. C. E. Black of this laboratory has supplied a tentative answer in the form of a "waxiness index." This index is the ratio of the modulus in tension, M_i, to the square of the modulus in shear, G. It arranges many yarns in a logical order, as shown in Table VI.

The waxiness index is a semi-empirical relationship which was developed from the following considerations: It was assumed that when the fingers pass over a fabric, a sense of waxiness is gained if the surface layers of the individual fibers are sheared by the movement of the fingers. It would follow rom this that waxiness is associated with ease of shearing, and is thus some function of the reciprocal of the shear modulus. For simplicity, we may assume the function to be $1/G$. Further, a tensile modulus that is low relative to the shear modulus would allow the fiber material to elongate and thus escape the shearing tendency. Therefore, a high ratio of M_i/G is to be associated with high waxiness. Combining the two factors:

$$\text{Waxiness index} = M_i/G^2.$$

Friction

Various measurements of fiber-fiber friction [16, 17] and fabric-fabric friction [10] have been reported. Further work is necessary to determine the relationships between surface smoothness, the coefficients of friction, and "waxiness." There is considerable doubt that the entire "feel" of stroking the fingers over a fabric can be described by a coefficient of friction. A velvet and a satin may have equal coefficients of friction and yet feel different because of the brushiness of the former.

TABLE VII. COEFFICIENTS OF FRICTION (FABRICS VS. LEATHER)

Material	Subjective rating of smoothness	Static coefficient of friction (μ)
66 Nylon	2.1 ± .8	.62 ± .03
Viscose rayon	1.8 ± .7	.60
Acetate rayon	2.2 ± 1.0	.59
Experimental fiber	3.7 ± .4	.46
Polyethylene	5.0 ± 0	.35

In measuring fabric friction, a piece of soft cowhide was used to approximate the human skin; this material was designated the "standard hand." This was mounted on a moving platform of Lucite. The fabric sample, mounted on a Lucite panel 3 cm. × 3.5 cm., was laid on the leather face down and loaded with a 180-g. weight. The force parallel to the fabric face was measured by means of a strain gage upon which the fabric block pulled.

A series of 5 twill fabrics was selected and 10 observers were asked to rate these from low to high in smoothness, assigning the numbers 1 to 5, respectively. These subjective ratings agree fairly well with the static coefficients of friction (see Table VII).

In another experiment, two pieces were cut from a tropical worsted and a nap was raised on one piece by means of a hand card. Everyone who examined these fabrics described the piece with the nap as being softer than the other. The coefficients of friction were measured under a 10-g. load (.95 g./cm.^{2}) with the result that the napped piece gave a higher value than the other (.67 and .63, respectively). Finally, a μ value of 1.31 was obtained on a piece of velvet under the 10-g. load. Most people would describe the surface feel of velvet as being very soft or smooth. We believe that softness of this type and smoothness and waxiness are three separate and distinct properties.

Contact Warmth

The term "contact warmth" is used to denote the initial, and often fleeting, sensation of warmth or coolness felt when a fabric is touched. A metal object at room temperature gives a pronounced sensation of coolness to the touch. When a wooden object is touched, this impression is more fleeting,

TABLE VIII. CONTACT WARMTH

Warm feel	Cold feel
Low heat capacity	High heat capacity
Low conductivity	High conductivity
Small area of contact	Large area of contact

less intense, or perhaps even absent. This situation is reversed when the temperature of the room and of the objects in it is higher than the body temperature. On an extremely hot day, for example, metal objects feel hotter than wooden objects, even though their actual temperatures are the same. This phenomenon is almost certainly a function of the heat capacity and of the heat conductivity. It seems logical, therefore, that the sensation of coldness or of warmth is due to the momentary persistence of a temperature differential between an object and the fingers. In fabrics especially, a third factor is the area of contact between the fingers and the fabric. These three factors are listed in Table VIII.

We have recently examined *films* instead of fabrics to see if they vary with regard to this particular kind of hand. Several observers independently picked polyethylene, nylon, and cellulose acetate films, in that order, for coldness, with polyethylene by far the coldest. The thermal data are given in Table IX.

The specific heat of polyethylene terephthalate is .32 cal./g. °C. Films made of it feel at least as warm as, and perhaps warmer than, cellulose acetate films. A preliminary value of .36 for Orlon acrylic fiber makes it also appear satisfactory on this score.

It should be mentioned that Rees has described a method for measuring the contact warmth of fabrics [24] without, however, offering any explanation for the differences observed.

Drape

The draping quality of fabric has been rather thoroughly treated by Peirce [19].* The test employed is the same as that for flexural rigidity—namely, the hanging-heart test. The quantity measured, however, is the length of fabric which will bend under its own weight to a certain degree. This bending length increases with increasing rigidity, and decreases with increase in weight per unit area. The equation for the bending length, c, is

$$c^3 = G/w,$$

where G is the flexural rigidity, and w is weight per unit area. The quality of drape refers to the ability of the fabric to form curves which are pleasing to the eye. A fabric with a low c value will hang straight down when unimpeded and will bend sharply around obstructions; a fabric with a high c value will not conform sufficiently to the curves of the body. For these reasons, fabrics with *intermediate* values of c should be the most attractive. Naturally, the optimum value of c will depend upon the type of goods and the purpose for which it is intended—for example, a representative cotton shirting gave a c value of 1.3 cm., a number of high-quality men's worsted suitings fell between 1.5 cm. and 1.7 cm., and single-weave overcoatings measured around 2.0 cm.

The factors responsible for the bending length are precisely those which give rise to the flexural rigidity, plus the rather obvious factor of fabric weight per unit area. The actual draping at any point in a garment depends upon one other factor—namely, the *total weight* suspended from that point.

* A rather different approach to this subject has appeared recently [8].

TABLE IX. CONDUCTIVITY AND SPECIFIC HEAT

	Polyethylene	Nylon	Cellulose acetate
Relative thermal conductivity	1.3	1.1	1.0
Specific heat (cal./g. °C)	.55	.43	.35

Smoothness and Luster

The visual smoothness, or lack of it, is the one property next to color which fascinates designers the most. There are many ways of avoiding smoothness—exemplified in crêpes, seersuckers, tweeds, corded and ribbed fabrics, piqués, bouclés, slubbed fabrics, and many other fabrics. On the other hand, the super-smooth effect of a mirror-like surface is sometimes sought, such as in a rayon satin. These are all mainly effects of fabric architecture, although the light-reflecting quality of the fibers plays a role. Two analyses of this subject have appeared recently [5, 22].

Covering Power

The visual covering power of a fabric depends partly upon the coverage (see page 71), partly on nap or fuzz, and partly on the transparency of the fibers. Two swatches of a rather open construction, identical in every detail except that one is dyed and the other is not, may be used to show that the dyed sample has much more covering power than the other. For this reason, covering power may also be increased by the use of delusterants or by roughening the surface of a fiber.

Contour Retention and Resilience

One of the most practical aspects of the resilience of fabrics has to do with shape retention, a subject which has given rise to an extensive literature (see, for example, [4, 9, 12]). If we iron a fabric flat, we wish it to stay that way, even though it may be a soft fabric. If we iron in a pleat or a crease, we want it to be retained. Wool exhibits this property of shape retention to a high degree in three rather different ways. The differences depend upon a time scale.

If a piece of gabardine or tropical worsted is momentarily crushed and then released, the fabric very quickly jumps back to its original condition. This is practically immediate recovery and underlies the liveliness quality. If the fabric is held crushed in the hand for about a minute and then released, it will be slightly mussed or wrinkled. However, after a moment or so, the wrinkles disappear. This phenomenon is due to fast recovery and underlies wrinkle-resistance. A third type of recovery is of the slow or longer-time variety. If a necktie is worn all day, it will be wrinkled under the knot. In a good wool necktie, these wrinkles will disappear overnight. Because of this, wool is used in the lining material of silk neckties. Thus, wool is a remarkably lively and crease-resistant material.

The above relationships illustrate why stress-strain studies must be expanded to stress-strain-time studies, not only in the case of fibers, as is now generally done, but in the case of fabrics as well. The many fiber studies which have been published cover collectively the presently-realizable time scale, from sonic frequencies at one end to creep and creep recovery at the other. In fact, publications in this field are so numerous that reference is given here only to several from this laboratory which have been especially utilized in the present work [2, 3, 18, 23]. We have varied the time scale in fabric testing from a fraction of a second in the liveliness tester to hours or days in the wrinkle recovery test [13].

Finally, it should be mentioned that there have been a few preliminary attempts at correlating fiber recovery with fabric recovery [3, 12].

Summary

The hand, liveliness, and shape retention of fabrics are controlled in a large measure by 3 fiber properties: the initial stiffness; the change in stiffness as the deformation or the load is increased; and the recovery behavior when the load is removed.

While other factors such as fabric construction and interfiber friction are important, the majority of these additional factors exert only a modifying influence on the basic properties above. Quite often such influences are detrimental ones. They may either protect or impair the natural resiliency of a fiber, but they certainly do not generate it. Properties impaired in spinning or weaving may often be regenerated by proper fabric finishing.

Acknowledgment

We wish to thank J. W. Ballou, C. E. Black, Sarah K. Breslin, H. J. Kolb, and members of the Development Section, Rayon Technical Division, for substantial contributions to this work. Part of the experimental work was carried out under the supervision of these persons, and part was performed by the Pioneering Physical Test Laboratory, under the supervision of C. J. Curtin.

Literature Cited

1. Backer, S., Relationship Between the Structural Geometry of a Textile Fabric and Its Physical Properties, Part I, TEXTILE RESEARCH JOURNAL **18**, 650 (1948).
2. Ballou, J. W., and Smith, J. C., Dynamic Measurements of Polymer Physical Properties, *J. Applied Phys.* **20**, 493 (1949).
3. Beste, L. F., and Hoffman, R. M., A Quantitative Study of Resilience, TEXTILE RESEARCH JOURNAL **20**, 441 (1950).
4. Buck, G. S., Jr., and McCord, F. A., Crease-Resistance and Cotton, TEXTILE RESEARCH JOURNAL **19**, 216 (1949).
5. Buck, G. S., Jr., and McCord, F. A., Luster and Cotton, TEXTILE RESEARCH JOURNAL **19**, 715 (1949).

6. Cassie, A. B. D., Physical Properties of Fibers and Textile Performance, *J. Text. Inst.* **37**, P154 (1946).
7. Chadwick, G. E., Shorter, S. A., and Weissenberg, K., A Trellis Model for the Application and Study of Simple Pulls in Textile Materials, *J. Text. Inst.* **40**, T111 (1949).
8. Chu, C. C., Cummings, C. L., and Teixeira, N. A., A Study of the Factors Affecting the Drape of Fabrics, TEXTILE RESEARCH JOURNAL **20**, 539 (1950).
9. Dillon, J. H., Resilience of Fibers and Fabrics, TEXTILE RESEARCH JOURNAL **17**, 207 (1947).
10. Dreby, E. C., A Friction Meter for Determining the Coefficient of Kinetic Friction of Fabrics, *J. Research Natl. Bur. Standards* **31**, 237 (1943).
11. Finch, R. B., Compressional Behavior of Textile Materials, TEXTILE RESEARCH JOURNAL **18**, 165 (1948).
12. Gruntfest, I. J., and Gagliardi, D. D., Wrinkle Resistance of Fabrics, *Ind. Eng. Chem.* **41**, 760 (1949).
13. Hebeler, H. H., and Kolb, H. J., Measurement of Fabric Wrinkling, TEXTILE RESEARCH JOURNAL **20**, 650 (1950).
14. Hoffman, R. M., A Generalized Concept of Resilience, TEXTILE RESEARCH JOURNAL **18**, 141 (1948).
15. Lewis, E. V., A Fundamental Study of Some Fabric Properties, *Papers of AATT* **4**, 84 (1949).
16. Lindberg, J., and Gralén, N., Measurement of Friction Between Single Fibers, Part IV, TEXTILE RESEARCH JOURNAL **19**, 183 (1949).
17. Mercer, E. H., and Makinson, K. R., Frictional Properties of Wool and Other Textile Fibers, *J. Text. Inst.* **38**, T227 (1947).
18. O'Shaughnessy, M. T., An Experimental Study of the Creep of Rayon, TEXTILE RESEARCH JOURNAL **18**, 263 (1948).
19. Peirce, F. T., The "Handle" of Cloth as a Measurable Quantity, *J. Text. Inst.* **21**, T377 (1930).
20. Peirce, F. T., Geometrical Principles Applicable to the Design of Functional Fabrics, TEXTILE RESEARCH JOURNAL **17**, 123 (1947).
21. Pollitt, J., Geometry of Cloth Structure, *J. Text. Inst.* **40**, P11 (1949).
22. Quynn, R. O., Bernet, E. J., and Fischer, E. K., Gloss Measurements on Fabrics, TEXTILE RESEARCH JOURNAL **20**, 492 (1950).
23. Ray, L. G., Jr., Tensile and Torsional Properties of Textile Fibers, TEXTILE RESEARCH JOURNAL **17**, 1 (1947).
24. Rees, W. H., Transmission of Heat Through Textile Fabrics, *J. Text. Inst.* **32**, T194 (1941).
25. Rees, W. H., Over-All Specific Volume, Compressibility, and Resilience of Fibrous Materials, *J. Text. Inst.* **39**, T131 (1948).
26. Schiefer, H. F., The Compressometer, an Instrument for Evaluating the Thickness, Compressibility, and Compressional Resilience of Textiles and Similar Materials, *J. Research Natl. Bur. Standards* **10**, 705 (1933).
27. Schiefer, H. F., Evaluation of Crush-Resistant Finishing Treatments for Fabrics, *Am. Dyestuff Reptr.* **26**, 667 (1937).
28. Smith, Harold DeWitt, Textile Fibers: An Engineering Approach to their Properties and Utilization, *Proc. A.S.T.M.* **44**, 543 (1944).
29. Weissenberg, K., Use of a Trellis Model in the Mechanics of Homogeneous Materials, *J. Text. Inst.* **40**, T89 (1949).

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Glycosidic Methoxyl Groups in Methanolyzed Cellulose

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Abstract

Oxidation by a glycol-cleavage reagent has proved that the acid-labile methoxyl groups in methanolyzed cellulose are linked in glycosidic combination (1 per molecule), and not in an acetal structure, which would require 2 such groups per molecule. Evidence confirming the glycosidic structure was obtained by fractionating methanolyzed cellulose to the point where number-average molecular weights must be calculated on the basis of 1 methoxyl group per molecule.

The rate of removal of methoxyl groups from methanolyzed cellulose upon acid hydrolysis was reinvestigated. The rate is roughly comparable to the rate of hydrolysis of methyl glucopyranosides. These findings contradict the basis for a claim, based on copper-number determinations, that the methoxyl groups of methanolyzed cellulose are very rapidly hydrolyzed and are of the acetal type.

ACID-LABILE methoxyl analyses offer a convenient end-group assay for methanolyzed celluloses—one that will allow the calculation of number-average molecular weights, provided it is known with certainty whether such groups are bound in glycosidic combination (1 group per molecule) or in an acetal structure (2 groups per molecule). There is no record in the literature of the formation of dimethyl acetals by aldohexoses on reaction with acid methanol; indeed, when prepared by other reagents, aldose dimethyl acetals are unstable in acid methanol, changing rapidly to methyl glycosides; hence, the glycosidic structure for the methoxyl group is more likely than the acetal structure.

Experimental proof of the glycosidic structure has been obtained by oxidizing methanolyzed cellulose with a glycol-cleavage reagent and observing that the methoxyl is very largely retained by the cellulosic material. Confirmation of the glycosidic structure so established was obtained by comparing the number of end-group methoxyls with the viscometrically determined molecular size of fractionated celluloses having relatively homogeneous chain lengths. Furthermore, the rate of acid hydrolysis of methoxyl groups from methanolyzed cellulose was determined and was found to be of the same order of magnitude as the rate exhibited, in homogeneous solution, by the methyl *D*-glucopyranosides.

* One of the laboratories of the Bureau of Agricultural and Industrial Chemistry, Agricultural Research Administration, U. S. Department of Agriculture.

Retention of Methoxyl After Glycol Cleavage

Periodate oxidation of methanolyzed cellulose would yield products of markedly different methoxyl content depending upon whether the methoxyls were combined in the acetal structure (formula I) or the glycosidic structure (formula III). Oxidation of I would yield II, with removal of methoxyl from the cellulose. Oxidation of III would give IV, retaining methoxyl.

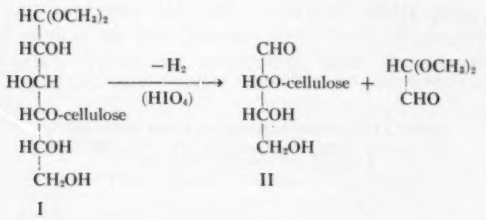
From the following experiments it appeared that periodate oxidation of methanolyzed cellulose proceeded according to scheme III→IV. Each of 3 samples of methanolyzed cotton linters (approximately 1.62 g. anhydrous weight), each containing 0.21% acid-labile methoxyl, was placed in a flask together with 10 ml. of 20% sodium acetate solution; 2, 5, and 10 millimols of aqueous periodic acid, respectively; and sufficient water to bring the volume in each flask to exactly 50 ml. The flasks were kept in a thermostat at 20°C for 5 days, after which each solution was analyzed for unconsumed

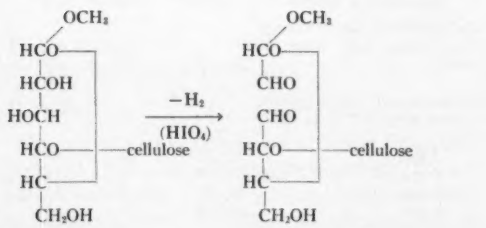
TABLE I. METHOXYL CONTENT AFTER OXIDATION OF CELLULOSES WITH PERIODIC ACID

Extent of oxidation (mols HIO_4 per mol glucose anhydride)	Methoxyl (%)
Methanolyzed cotton linters	
none	.21, .21
0.20	.19, .20
0.46	.20, .18
0.83	.18, .15
Purified cotton fiber	
none	none
1.08	<.01, <.01

periodic acid, and the extent of oxidation was calculated. The insoluble oxidized celluloses were removed by filtration, rinsed, air-dried, and analyzed for moisture and methoxyl. A similar experiment in which cotton fiber replaced the methanolyzed linters showed that no methoxyl was formed during the oxidation. The results of these experiments are presented in Table I. All methoxyl analyses reported herein were obtained by the method described by Hoffpauir and Reeves [2], and the results are expressed on an anhydrous basis.

Since the methoxyl groups are located on the chain ends that are available to the oxidant, had they been combined as acetal all of the methoxyl should have disappeared in these experiments. The complete removal of methoxyl by the scheme I→II





would have required only 0.034 millimols of periodate per g. (0.0055 mols periodate per mol glucose anhydride). Actually, no significant change in methoxyl content was noted except for a small loss in the most drastically oxidized sample (83% oxidized). This sample lost 30% of its weight due to increased water solubility after oxidation; hence, the small loss of methoxyl may be attributed to the selective dissolution of the shortest chain molecules (those highest in end-group methoxyl content) after oxidation.

Fractionation to Approximately Equal Number- and Weight-Average Molecular Sizes

Fractionation of cellulose to approximately uniform molecular size would yield a sample having a number-average molecular weight only slightly lower than its weight average. In the limiting case of a single molecular species the two weights would be identical, and in no case could the number-average weight exceed the weight average. The latter restriction makes it possible to demonstrate the presence of glycosidic methoxyl groups in fractionated methanolyzed celluloses.

Four different methanolyzed cotton celluloses were fractionated in the following manner: The celluloses were stirred at 0°C with 10*N* sodium hydroxide solution, allowing 5 to 7 ml. of alkali for each gram of cellulose. To the slurry 4 volumes of ice water were added, with stirring, during the course of 15 min. The suspensions were centrifuged, and the sediments rinsed with cold 2*N* sodium hydroxide, water, dilute acetic acid, and finally with distilled water until the conductivity of the rinse water approached that of distilled water.

TABLE II. PROPERTIES OF THE ALKALI-INSOLUBLE FRACTIONS OF SOME METHANOLYZED COTTON CELLULOSES

Methoxyl* (%)	Intrinsic viscosity†	Weight-average D.P.‡	Calculated number-average D. P. allowing: 1 methoxyl per molecule	2 methoxyls per molecule
.050	1.79	465	380	760
.085	1.14	296	225	450
.113	.71	185	169	338
.18	.52	135	106	212

* Average value.
† In A.C.S. standard cuprammonium.
‡ Obtained by multiplying intrinsic viscosity by 260; *cf.* Kraemer and Lansing, *J. Phys. Chem.* **39**, 153 (1935).

The insoluble cellulosic fractions were then rinsed with alcohol followed by ether, and after drying were subjected to methoxyl analyses and viscometric measurements in cuprammonium solutions—the former to determine number-average; the latter, weight-average molecular sizes.

The number-average degrees of polymerization calculated from the methoxyl content allowing 1 and 2 methoxyls per molecule are compared in Table II with the viscometrically determined weight-average degree of polymerization. It is apparent that allowing 2 end-groups per molecule yields number averages greater than the weight averages, a situation which is theoretically impossible. On the other hand, allowing but 1 end-group per molecule yields number averages slightly lower than the weight averages, which is in agreement with requirements for a cellulose preparation that is relatively homogeneous as to chain length.

Hydrolysis of Methoxyl Groups from Methanolyzed Celluloses

The results presented in the two preceding sections require reconsideration of the work of Mehta and Pacsu [3], who have stated that the methoxyl groups in methanolyzed cellulose are combined in acetal linkages. These workers investigated the rate of hydrolysis of methoxyl groups from methanolyzed cellulose, but they did not analyze for methoxyl in their hydrolyzed preparations; instead, they determined copper numbers and drew conclusions as to methoxyl content from the copper numbers. Because the copper number of their methanolyzed cellulose increased rapidly upon hydrolysis, Mehta and Pacsu assumed that methoxyl groups were being rapidly removed by the aqueous acid. On this basis they stated that the methoxyl groups were of the acetal type. Copper numbers do not constitute a reliable quantitative measure of methoxyl in cellulose. Obviously, reducing action can be increased by the rupture of any linkage in the cellulose; therefore, increase in copper number should not be taken as evidence for the hydrolysis of methoxyl groups. That some hydrolysis occurs at positions other than the methyl glycoside groups is indicated by D.P. estimations given in the last columns of Tables III and IV.

Results given in Tables III and IV showed that methoxyl groups were only slowly removed by normal hydrochloric acid at 60°C, although there was, indeed, a pronounced increase in copper numbers. Four-gram samples of methanolyzed cellulose were introduced into 200 ml. of 1*N* aqueous hydrochloric acid that had previously been brought to 60°. The samples were placed in a thermostat maintained at 60° ± 0.2°C for various lengths of time, after which they were withdrawn, filtered, rinsed, and dried. These samples were analyzed for methoxyl, and copper numbers were determined by the method of Heyes [1]. In both instances (Tables III and IV) it is evident that the methoxyl groups have half-life periods of 100 hrs. or greater under the standard conditions of hydrolysis. Therefore, these results are not in agreement with the conclusions of Mehta and Pacsu, who stated, on the basis of copper-number determinations, that methoxyl was almost completely removed at the end of 72 hrs. under these conditions. Half-life values of the magnitude found in the present work are in agreement with those anticipated for methyl gluco-

TABLE III. HYDROLYSIS OF PURIFIED COTTON CELLULOSE METHANOLYZED AT 0°C FOR 24 HRS. WITH 43% HCl IN MeOH

Treatment of sample	Methoxyl (%)	Copper number	Weight-average D.P.*
Methanolyzed only	.09, .08	2.3	225
Methanolyzed, then hydrolyzed with *N* HCl at 60°C for:			
1 hr.	.08, .07	2.0	230
6 hrs.	.08, .07	2.4	226
24 hrs.	.07, .07	3.3	216
96 hrs.	.06, .06	4.2	211

* Estimated as in Table II.

TABLE IV. HYDROLYSIS OF MERCERIZED COTTON CELLULOSE METHANOLYZED AT 30°C FOR 500 HRS. WITH 0.5*N* HCl IN MeOH

Treatment of sample	Methoxyl (%)	Copper number	Weight-average D.P.*
Methanolyzed, then extracted for 2 hrs. with water at 60°C	.32, .31	0.1	139
Methanolyzed, then hydrolyzed with *N* HCl at 60°C for:			
2 hrs.	.32, .33	0.3	136
8 hrs.	.28, .33, .28, .33	1.1	132
24 hrs.	.30, .29	1.4	131
72 hrs.	.25, .26	2.3	131

* Estimated as in Table II.

pyranoside structures in cellulose [3] and with those found for methyl α- and β-*D*-glucopyranosides in homogeneous solution [4].

Acknowledgment

The authors are indebted to B. T. Barrett and Wilhelmina Schwartz for assistance in the preparation of some of the samples.

Literature Cited

1. Heyes, T. F., *J. Soc. Chem. Ind.* **47T**, 90 (1928).
2. Hoffpauir, C. L., and Reeves, R. E., *Anal. Chem.* **21**, 815 (1949).
3. Mehta, P. C., and Pacsu, E., TEXTILE RESEARCH JOURNAL **19**, 625 (1949).
4. Moelwyn-Hughes, E. A., *Trans. Faraday Soc.* **25**, 81, 503 (1929).

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Letters to the Editor

Short communications in the form of Letters to the Editor are intended to provide prompt publication of significant new research results and to permit an exchange of views on papers previously published in the JOURNAL. These communications are not submitted to formal review as are research papers, and the editors do not assume any share of the author's responsibility for the information given or the opinions expressed. When work previously published in the JOURNAL is the subject of critical comment, the authors of the original paper are given an opportunity to submit a reply, which will be published concurrently when possible.

The Reaction Between Methanol and Hydrogen Chloride at 0° C

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New Orleans, Louisiana
September 11, 1950

To the Editor
TEXTILE RESEARCH JOURNAL

Dear Sir:

In a recent communication in TEXTILE RESEARCH JOURNAL [1] dealing with the methanolysis of cellulose it was stated that a reagent containing 43% hydrogen chloride in methanol was checked and no significant loss of hydrogen chloride was detected after 28 days at 0°C. This statement implied that the reaction

$$CH_3OH + HCl \rightarrow CH_3Cl + H_2O$$

does not proceed at an appreciable rate at 0°C.

Recorded here are the results of a series of experiments in which, on the contrary, the loss of hydrogen chloride under such conditions was detectable and appreciable amounts of water were formed as a result of the reaction.

In the work referred to above high copper numbers were observed for the methanolyzed celluloses. It is suggested that this reducing action may have resulted from a side reaction—namely, hydrolysis by the water formed in the reagent during the prolonged treatment of the cellulose. It has already been shown that cellulose methanolyzed under an-

TABLE I. REACTION BETWEEN HYDROGEN CHLORIDE AND METHANOL AT 0°C

Hydrogen chloride			Water		
Initially (g./l.)	After 7 days (g./l.)	After 45 days (g./l.)	Initially (g./l.)	After 7 days (g./l.)	After 45 days (g./l.)
150	148	139	4.5	4.5	9.0
380	372	333	5.0	7.3	30.0
440	430	*	4.5	9.0	31.5*

* This sample could not be pipetted accurately due to the evolution of bubbles of gas. A qualitative test for methyl chloride was positive.

hydrous conditions has a very low copper number, and that methanolysis in the presence of small amounts of water yields higher copper numbers [2].

Experimental

Anhydrous hydrogen chloride was passed from a tank through a sulfuric acid trap into an empty trap, then into commercial methanol cooled in an ice-salt bath. The temperature of the solution was kept between −5° and 0°C during the introduction of the gas, and it was not at any time allowed to rise above 0°C.

Samples were analyzed for water or hydrogen chloride after pipetting known volumes of solution into excesses of anhydrous pyridine or standard alkali, respectively. Water was determined by the Karl Fischer technique; hydrogen chloride, by back titration with standard acid. Glassware employed in the water determinations had been oven-dried and allowed to cool in a desiccator. The methanol employed as starting material contained 2.08 g. water per liter.

Samples found to contain 150, 380, and 440 g. hydrogen chloride per liter were analyzed for water and were sealed in long-necked glass vials without warming the contents above 0°C. The vials were placed in an ice-water bath in a Dewar flask which was stored in a refrigerator. After 7 days the vials were momentarily opened for removal of samples for analysis; again after 45 days samples were analyzed for water and for hydrogen chloride.

The results of these experiments are given in Table I. It is apparent that there was an appreciable loss of hydrogen chloride from all of these solutions. From a plot of the values given in the last line of Table I it is apparent that a solution containing, initially, 440 g. hydrogen chloride per liter, after 28 days at 0°C would contain approximately 2% water. It is noteworthy that the solution which contained, initially, 380 g. hydrogen chloride per liter, after 45 days lost 1.29 mols of hydrogen chloride and gained approximately the same amount (1.39 mols) of water.

Literature Cited

1. Mehta, P. C., and Pacsu, E., TEXTILE RESEARCH JOURNAL **19**, 625 (Oct. 1949).
2. Reeves, R. E., Schwartz, W. M., and Giddens, J. E., *J. Am. Chem. Soc.* **68**, 1383 (1946).

RICHARD E. REEVES
CARROLL L. HOFFPAUIR
ROBERT J. DEMINT

Types and Dimensions of Fiber Scales from the Wool Types of Domestic Sheep and Wild Life

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Abstract

Scale structure and dimensions and fiber thickness were measured on a number of fibers representing the different fiber types from fleeces of several wild life species, including the Big Horn sheep, and of fibers from the various wool types of domestic and primitive sheep, including the fine-wool, medium-wool, long-wool, and mixed-wool types. The scale index, or relation of scale height to fiber thickness, was studied as a means of identification of fiber types and as a breed characteristic. The relationship between scale structure and dimensions in the various animal textile fibers and the identification of the animals from which the fibers came were studied.

Introduction

The study of the surface structure of wool and hair fibers is an important aid in the identification of fiber types. Besides affording a knowledge of fiber types, such a study would help determine the "healthy" state of fibers with respect to the number of scales per unit length and their shape and dimensions. The visible scale height seems to be an important characteristic for differentiation between wool and related hair fibers such as mohair and camel's hair. A special study of the epidermal structure is sometimes necessary in blends of wool and related fibers which can only be distinguished by the difference in the scale formation.

Apart from ascertaining the number of scales per unit length of the fiber and their shape in relation to the felting properties of wool, some workers have tried to relate these characteristics to the different species or breeds of sheep. A study of the surface scales—the form and surface dimensions of the scales—was made on fibers from a number of different wool samples representing different breeds and countries, including some wild sheep. The study included determinations of the number of scales per unit length of the fiber, the scale formation or outline, and the scale height, with some dimensional measurements; the object was to ascertain whether these characteristics were: (*a*) related to different species or breeds of sheep; (*b*) specific for different wool types; (*c*) specific enough to enable identification of fiber types in mixed wools.

All classes of wools, such as fine, medium, long, crossbred, and carpet types, were represented in the study; in the case of mixed wools, the different types of fibers, such as true wool, hair, and hemp, were examined separately.

Classification of Scale Structure

Various workers have tried to classify scale structure by a description of their general outline. Blyth [1] described two types of scale structure on the wool fibers—the wool type and the reticulate type. The former in its simplest form is of coronal pattern, each scale encircling the shaft of fiber and resting in the cup formed by the scale beneath it. In very fine fibers, the ectal edge of the scales is convexly curved, is faintly and irregularly serrate, and points distally. In thicker fibers, more than one scale to the circumference can be seen; these tend to be broad and shallow, and are either convexly curved or their free edges trace out a wave-shaped line around the fiber shaft.

The reticulate or hair type of scale structure has the appearance of a rather taut net stretched across the surface of the fiber. The scales, although slightly curved, appear rather straight and smooth-sided in comparison with those of the wool type. More than two scales meet at a point, and they are often irregular in size and shape.

Hausman [8], from his study of mammalian hair fibers, formulated his well-known classification dividing the scale structure into coronal and imbricate

forms. The coronal scales completely encircle the cortiçle cylinder of the hair shaft, their free ectal edges sculptured in various forms. The imbricate scales do not individually encircle the corticle cylinder, but are arranged like the scales of a fish, with their free distal edges etched into different shapes. The two groups of scales are further classified according to their apparent structure. The coronal scales may be simple, serrate, and dentate; imbricate scales may be ovate, acuminate, elongate, crenate, and flattened. Although the author did not include wool in his studies, the crenate and flattened types are often encountered on wool fibers.

Review of Literature

Although scale structure has not been studied extensively in the field of wool technology, various workers have been interested in the examination of scale structure. Their methods may be classified under three main headings—direct examination of the fiber under the microscope; half-mounting in media of refractive index similar to that of the fibers; and impression or cast methods in quick-drying media.

The direct examination of the fibers under the microscope was unfavorable because of the non-availability of suitable mounting media, and the optical difficulty in focussing wool due to its tri-dimensional character.

Half-mounting in media of refractive index similar to that of the fibers was used to overcome some of the above-mentioned difficulties. By immersing the fibers halfway in a mounting liquid, the lower part of the fibers becomes invisible because of the liquid; only the fiber surface facing the observer is visible and can be studied. Different media and techniques have been employed by Manby [14], Reumuth and Schwerdiner [18], and Herzog [10], with satisfactory results.

The cast or impression method involves obtaining imprints of the surface structure in a suitable quick-drying media, and then studying the imprints under the microscope or by projection. Various media, such as resin, fingernail polish, cellulose, gelatin, and thermoplastic film, have been suggested by different workers. Saxinger [19], Herzog [9], Von Bergen and Mauersberger [21], Lockte [13], Hardy [4], Hardy and Plitt [5], Koonz and Strandine [11], and Wildman [22] employed different techniques to get cast impressions.

Earlier workers, such as Brevoort [2], McMurtrie [16], Hausman [6], and Manby [14], used special staining techniques for the study of scale structure; these methods have lost popularity due to improvement of the impression method. Only a few references are available regarding the specific scale patterns of different fibers.

Hausman [6], while classifying the scale forms [8] from his drawings of the hairs of 166 fur-bearing animals [7], was able to find an interesting and surprising relationship in the scales of infrahominid mammals—namely, that the size of the scales (*i.e.*, their anteroposterior width) and their forms varied together in a constant way. Moreover, the size (and hence also the forms) of the scales bore a relationship not to the species of mammals bearing the hair but to the diameter of the hair shaft bearing the scales. In the finest and the softest hairs, only the coronal type of scales is found. In fibers less than 8.50 μ in diameter the scales are coronal, while in fibers coarser than this they are imbricate. Hausman found that there was a decrease in the "scale index" $\left(\frac{\text{scale height}}{\text{diameter}}\right)$ in the fibers as the diameter increased. This indicated that there was a pulling-out of the scales with increase in diameter. He also found that cuticle scales may vary according to the cross section of the fiber. In circular and eliptical cross sections, the form is different from that in a flattened cross section, which is like a duck bill where the tip has a flattened portion and is different from the middle and base. The differences in form, according to Hausman, are the results of the differences in the gradual drying-out of the hair shaft plus the effects of wear on the free ectal edges of the scales, particularly at the tips of the shaft.

Litterscheid and Abeler [12] modified the method of accentuating the scales by preliminary treatment of the fibers: by bleaching pigmented hairs, if necessary, with 10% hydrogen peroxide for from 3 to 7 days; or by soaking the fibers in 60% to 63% nitric acid for 6 hrs. and drying. They stained the fibers with carbol fuchsin so that a deposit of dye was left along the edges of the scales on drying. From drawings of this material they delineated and described in detail parts of the hairs of fur-bearing animals.

Butarin [3] made a study of cuticular scales of the fleeces of wild sheep (Argali Arhar) and local fat-rumped sheep in Russia (Kirghiz sheep), and

noticed that the cuticular scales of kemp fibers are polyhedral, mostly hexagonal, and form a regular symmetrical pattern. The transitional and downy fibers were found to have annular scales. He stated further that the scales of wild sheep resemble one another but differ from those of domestic sheep.

Skinkle [20], from the measurement of visible scale height and the quantity S^3/D, where S represents the scale height and D the diameter of the fiber, was able to differentiate between wool and mohair fibers as follows:

1. The value of S is below 17.0 μ in the case of wool fibers.
2. The value of S is above 18.5 μ in the mohair fibers.
3. If the value of S is between 17.0 μ and 18.0 μ, the hair is probably wool. This could be verified by determining the value of S^3/D, which is below 140 for wool fibers.
4. If the value of S is between 18.0 μ and 18.5 μ, the hair is probably mohair. This could be verified by calculating the value of S^3/D, which is above 160 for mohair fibers.

Skinkle stated further that no cases had arisen in his experience which did not fall into one of the above classes, but it is possible that some wools may have values of S slightly above 18 μ but values of S^3/D of 140 or less.

Mirzoeva [17] made microscopic investigations of the form and development of the scales of the wool of purebred Merino, Turkmenian fat-rumped, Iomud, and Erek sheep, and concluded that the number of scales for a given length of wool (256 μ) and the form and area (in μ^2) are specific to the individual breeds studied and must be regarded as genetically controlled. He stated further that, contrary to the findings of D. Udolskii (whose methods were used in his study), no definite influence of breed on the number of rows of scales on a hair could be ascertained.

Mathews [15] stated that the number of scales necessary to cover the circumference of the fiber varies considerably, depending upon the diameter of the fiber. The average height of the scales is approximately 28 μ and the average width approximately 36 μ. In the finest wools each one of the scales is large enough to encircle the shaft of the fiber, but with increased fiber diameter the number of scales necessary to cover the circumference increases proportionately. Mathews further asserted that the visible scale height in fine wools is from 8 μ to 10 μ and in coarse wools it may increase to 18 μ. The number of scales along the edge of the fiber per 100 μ length averages 10 or 12, but may range from 6 to 14.

The origin of the samples used in the present study are given in detail in Appendix Table I and may be summarized as follows:

Fleece type	No. of samples by origin				
	U.S.	England	Asia	Australia	Total
Wild life	4	0	0	0	4
Fine-wool breeds	2	0	0	1	3
Medium-wool breeds	10	2	0	0	12
Long-wool breeds	4	2	0	0	6
Crossbred breeds	3	0	0	0	3
Mixed-wool breeds	1	4	28*	0	33
Totals	24	8	28	1	61

* India —12 samples.
China — 9 samples.
Turkey— 4 samples.
Austria— 1 sample.
Russia — 2 samples.

Preparation of the Samples and Method of Study

Samples from which representative fibers were taken for the study of surface scale structure were first scoured by the emulsion method, using soap and soda, and then rinsed in water. After drying at room temperature, they were given a bath in carbon tetrachloride.

Hardy and Plitt's [5] thermoplastic film technique was followed for determining the surface scale structure on the different types of wool. Impressions were obtained of representative fibers, and photomicrographs were prepared with the help of a projector with a magnification of 500×. The following measurable characters were studied:

1. Form and outline of the scales.
2. Number of scales per 1-in. length of the fiber along one surface.
3. Number of scales per 1-in. length and 100 μ width of the fiber, calculated to facilitate a better comparison of different wools on a standard basis.
4. Average scale height in different types of wool.
5. Number of scales per 100 μ length along the margin of the fiber.
6. Diameter of the fiber (on the photomicrograph).

7. Relation of scale height to fiber diameter, $\frac{S}{D}$, which Hausman [8] designated as the scale index in his study of fur fibers. The types of scale outline were classified according to that described by Blyth [1] and Hausman [8].

The number of scales per unit length of the fiber were counted (from the photomicrograph) along one surface of the fiber. The number of scales represented the number of complete scales plus half the number of fractional scales.

The measurements of scale height and diameter were made with a millimeter scale on the magnified image. The average scale height was calculated from 10 scales taken at random.

The number of scales per 100 μ length along the margin of the fiber, measured with the help of a millimeter scale, represented the number of scale heights in 50 mm. length along the margin.

The observations are recorded in Appendix Tables I–III.

Summary of Results

The results for the different types of wools are summarized below and on p. 87.

The scale outline of the wool fibers varied from coronal to imbricate forms (Figure 1), depending upon the thickness of the fibers. On hair fibers the reticulate form of scales was encountered in all cases, with polygonal and flattened types occurring (Figure 2). In the case of kemp fibers the scale outline was mostly of the flattened type, except for those for the wool types of European origin, which were of polygonal form, resembling a honeycomb structure. (See Figures 3–6.)

RESULTS FOR THE WOOL TYPE OF SHEEP, INCLUDING THE UNDERCOAT OF WILD LIFE AND THE WOOL FIBERS OF MIXED WOOLS

Sheep or wild life type	No. of scales: Per 1-in. length	Per 1-in. length and 100 μ width	Average scale height (μ)	No. of scales along margin per 100 μ length	Diameter of the fiber (μ)	Scale index $\left(\frac{\text{scale height}}{\text{diameter}}\right)$
Fine wools						
Average	2,283	15,937	13.2	8.3	14.6	0.906
Maximum	2,400	20,000	15.3	10	16.0	1.017
Minimum	2,200	13,750	12.0	6	12.0	0.750
Crossbred						
Average	2,550	11,107	12.3	8.7	24.0	0.518
Maximum	3,400	17,000	13.8	11	28.0	0.605
Minimum	2,200	7,857	9.7	6	20.0	0.489
Medium wools						
Average	2,283	9,502	13.8	8	25.8	0.572
Maximum	3,200	13,000	22.0	10	34.0	0.846
Minimum	1,000	5,555	10.1	4	18.0	0.361
Long wools						
Average	1,650	4,466	24.1	4.5	36.5	0.086
Maximum	2,700	6,750	30.0	5	42.0	1.000
Minimum	1,100	3,333	20.5	4	30.0	0.512
Mixed wools						
Average	1,969	11,833	14.9	6.8	17.3	0.893
Maximum	2,700	18,333	21.4	9.0	24.0	1.143
Minimum	1,200	6,000	11.2	4	12.0	0.559
Wild life (undercoat)						
Big Horn	2,400	20,000	12.8	9	12.0	1.066
Deer	2,800	28,000	10.1	10	10.0	1.010
Elk	2,700	20,769	11.0	10	13.0	0.916
Antelope	2,400	18,461	14.2	8	13.0	1.092
All wools						
Average	2,108	11,696	14.85	7.2	20.9	0.814

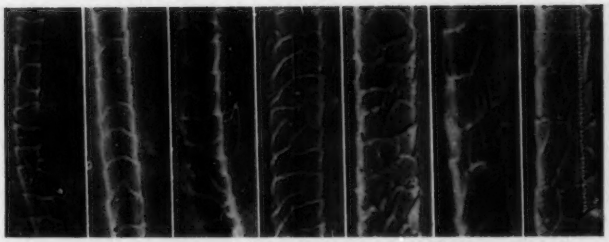

FIG. 1. *Common pattern of scales revealed by surface structure of wool fibers. Coronal, or wool type of scales, and imbricate forms are represented.*

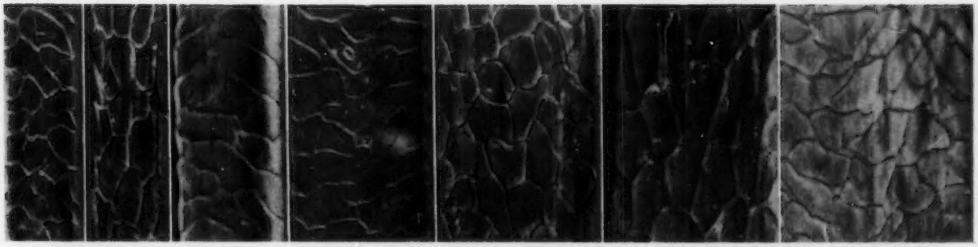

FIG. 2. *Common pattern of scales revealed by surface structure of hair fibers. Polygonal (penta- and hexagonal) and reticulate (flattened) forms are represented.*

RESULTS FOR TYPES OF FIBERS, INCLUDING THE OUTER COAT OF MIXED-WOOL SHEEP AND WILD LIFE, SUCH AS KEMP FIBERS (HAIR AND KEMP ARE FROM MIXED WOOLS)

Sheep type	No. of scales: Per 1-in. length	No. of scales: Per 1-in. length and 100 μ width	Average scale height (μ)	No. of scales along margin per 100 μ length	Diameter of the fiber (μ)	Scale index $\left(\frac{\text{scale height}}{\text{diameter}}\right)$
Wool						
Average	2,108	11,696	14.9	7.2	20.9	0.814
Maximum	3,400	20,000	30.0	11	42.0	1.143
Minimum	1,000	3,333	9.7	4	12.0	0.517
Hair						
Average	3,635	6,001	22.8	5.3	62.0	0.396
Maximum	5,400	10,285	39.5	9	128.0	0.538
Minimum	1,800	3,214	11.5	3	34.0	0.170
Kemp						
Average	5,383	3,664	18.9	6.8	162.5	0.110
Maximum	7,200	6,500	33.9	10	264.0	0.207
Minimum	3,500	2,500	10.7	4	74.0	0.064
Outer coat of wild life						
Big Horn	6,000	2,143	24.2	5	280	0.087
Deer	11,500	3,086	25.7	4	376	0.068
Elk	7,600	1,969	24.7	5	386	0.064
Antelope	14,000	2,661	21.2	5.5	526	0.040

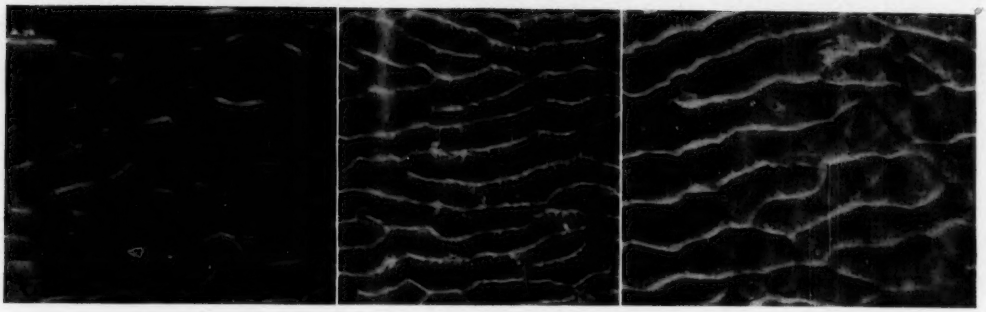

FIG. 3. *Scale type and surface structure of kemp fibers from Asiatic wools.* Left to right: *2 from India and 1 from China. All of flattened type.*

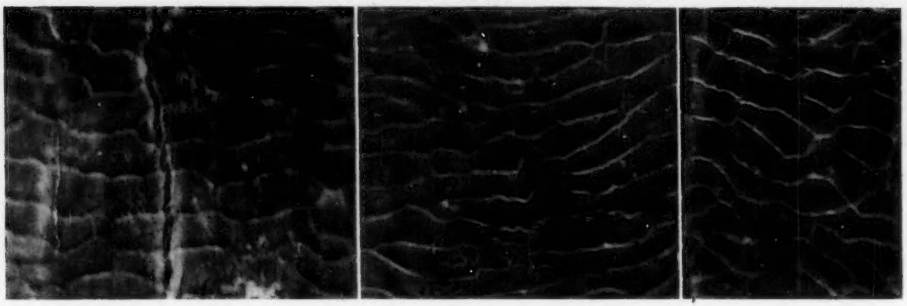

FIG. 4. *Scale type and surface structure of kemp fibers from 3 Asiatic (Turkey) wools. All of flattened type. The fiber on the left was cracked in preparation.*

Conclusions and Discussion

The following conclusions are evident from the study of surface scale structure in different types of wools:

1. The scale outline in wool fibers of all types can be classified according to the forms of scale structure described by Blyth [1] and Hausman [8]. Serrate and dentate types of scales among the coronal form, and ovate, acuminate, and elongate types of scales among the imbricate form, as described by Hausman [8] on the fur fibers, were not encountered on wool fibers of any type. It was revealed that the scale outline is more closely related to the diameter of the fiber than to the breed or fiber type. Irrespective of the breed or fiber type, the scale type tends to be annular or coronal (single scale across the width of the fiber) up to a diameter of 20 μ. As the diameter increases, the form becomes imbricate (more than one scale across the width) (Figure 1). In fibers of greater diameter, such as hair and kemp, the scales show various forms of reticulate and polyhedral structure (Figures 2–6). The scales are fairly regular in the individual fibers but are not specific for breed or fiber type. As the diameter of the fiber increases, the scale height decreases and the form appears to be more flattened than polygonal forms.

2. There is a wide range in the number of scales per 1-in. length of the fiber—the number may vary from 1,000 to 7,000. Irrespective of fiber diameter, the number is smaller in wool fibers (average 2,108) than in hair (average 3,635) and kemp (average 5,383). However, the number of scales per 1-in. length and 100 μ width of the fibers is larger in the wool fibers (average 11,696) than in

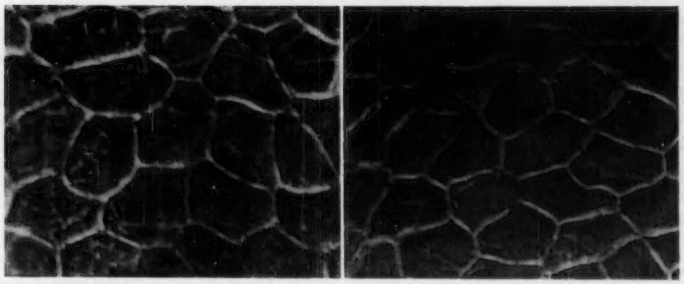

FIG. 5. *Scale type and surface structure of kemp fibers from European wools.* Left: *Herdwick.* Right: *Swaledale. Typical polygonal type resembling a honeycomb is shown.*

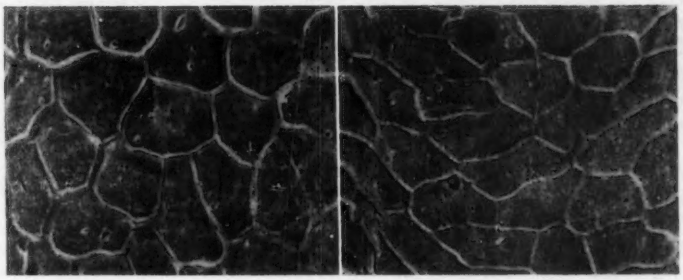

FIG. 6. *Scale type and surface structure of kemp fibers from European wools.* Left: *Scotch Blackface.* Right: *Welsh Mountain. Typical polygonal type resembling a honeycomb is shown.*

hair (average 6,001) and kemp (average 3,664). Thus, strictly speaking, the number of scales in wool fibers is larger than in hair and kemp. No relationship seems to exist between the number of scales per unit length and the wool type.

3. The average scale height in all types of wools ranged between 9.7 μ and 39.5 μ (average for wool, 14.85 μ; hair, 22.8 μ; and kemp, 18.9 μ). Contrary to the observations of Skinkle [20] that the average scale height of wool does not exceed 18.0 μ, some wool types showed maximum scale heights higher than this limit. Although, on the average, the limit was never exceeded in the fine, crossbred, or medium-wool types, when taken collectively, the average scale height was higher than the limit in the case of long wools (average 24.1 μ). In the case of hair fibers and kemp, the scale height exceeded 18.0 μ in many cases. It is therefore doubtful that this criterion for distinguishing between wool and mohair can be relied upon.

4. The number of scales along the margin of the fiber per 100 μ length varied from 3 to 11 for all wool and fiber types. The average number of scales on the wool fibers was 7.2; on the hair fibers, 5.3; and on the kemp fibers, 6.8.

5. The scale index [8] was calculated for all wools and fiber types. The range was from 1.143 (maximum for mixed wools) to 0.064 (minimum for kemp). The average scale index for all wool fibers was 0.814; for hair, 0.396; and for kemp, 0.110. There is a distinct difference in scale index between the different kinds of fibers; the scale index for the wool fibers ranged from 0.517 to 1.143; for the hair fibers, from 0.170 to 0.538; and for the kemp fibers, from 0.64 to 0.207. The ranges, as well as the averages, show that the scale index increases progressively in kemp, hair, and wool fibers. Thus, the scale indices differentiate between kemp, hair, and wool fibers but are not accurate for heterotypical fibers. Hausman [8] observed a similar relationship between scale index and diameter of fiber for fur fibers. With an increase in fiber diameter, irrespective of type, there is a corresponding decrease in scale index. The relationship is clearly shown in the Appendix Tables I–III, which include all of the wool and fiber types.

6. There seems to be no relationship of any of the attributes—number of scales per unit length of the fiber, average visible scale height, number of scales per 100 μ length along the margin, scale index

—to breed or wool type. The observation of Mirzoeva [17] that the number of scales for a given length of wool (265 μ) and the form and area (in μ^2) in the purebred Merino, Turkmenian fat-rumped, Iomud, and Erek sheep are specific to the individual breeds may be true because of the wide range of variation in the types. However, this generalization is not accurate when the types are more closely related.

7. From the different attributes studied for the scale structure, it appears that the undercoat of the wild species studied was very similar to the undercoat of mixed-wool sheep or the wool fibers of fine-wool breeds, and the outer coat is akin to thin kemp fibers of domestic sheep. The number of scales per 1-in. length and 100 μ width of the fiber was the largest on the undercoat fibers of the deer, numbering 26,000.

8. It is interesting to note that the scale structure of kemp fibers in the four mixed-type wools originating in England (Scotch Blackface, Herdwick, Welsh Mountain, and Swaledale) all showed a similar shape and form—the scales were hexagonal in shape and were combined in a honeycomb-like structure (Figures 5 and 6). On the other hand, kemp fibers from mixed type of wools from Asiatic countries all had the flattened and reticulate type of scales (Figures 3 and 4). It is probable that these special characteristics are related to the origin of domestic sheep in Europe and Asia. A study of the outer coat of Mouflon, Argali, and Urial sheep, and of kemp fibers from domestic sheep from these locations is suggested.

Literature Cited

1. Blyth, J. S. S., Studies on the Fleece Fibers of British Breeds of Sheep, *Z. Tierzücht. und Züchtungsbiol.* **7**, 3 (1926).
2. Brevoort, H. L., Fur Fibers as Shown by the Microscope (New York, 1886); quoted by Hardy, J. I., and Plitt M., (ref. [5]).
3. Butarin, N. S., A Comparative Study of the Fleece of Wild Sheep and the Kirghiz Fat Rumped Sheep (in Russian), *Trudy Kirgiz. Kompl. Eksp.* **4**, No. 3, 59–76 (1933–1934) (English abstract in *Anim. Breed. Absts.* **4**, No. 1, 44 (1936)).
4. Hardy, J. I., A Method for Studying the Scale Structure of Medullated and Pigmented Animal Fibers, *J. Text. Inst.* **23**, T1–5 (1932).
5. Hardy, J. I., and Plitt, M., An Improved Method for Revealing the Surface Structure of Fur Fibers, Wild Life Circular No. 7, U. S. Dept. of Interior, Washington, U. S. Govt. Printing Office, 1940.
6. Hausman, L. A., A Micrological Investigation of the Hair Structure of Monotremata, *Am. J. Anat.* **27**, 463–95 (1920).
7. Hausman, L. A., Structural Characteristics of the Hair of Mammals, *Am. Naturalist* **54**, 496–523 (1920).
8. Hausman, L. A., Recent Studies of Hair Structure Relationships, *Sci. Monthly* **30**, 258–77 (1930).
9. Herzog, A., Abdrücke tierischer Wollen und Haare in Harz, *Melliand Textilber.* **8**, 341 (1927).
10. Herzog, A., Microscopic Examination of Fibers: Simple Process for Semi-Imbedding, *Melliand Textilber.* **19**, 405–7 (1938).
11. Koonz, C. H., and Strandine, E. J., A Rapid and Simplified Method for Revealing the Surface Pattern of Hair (English translation), *Am. Microscop. Soc.* **64**, 63–4 (1945) (Abstract in *Anim. Breed. Absts.* **13**, No. 4, 183 (1945)).
12. Litterscheid, F. M., and Abeler, C., Über den Bau und die Erkennung von Tierhaaren, mit besonderer Berücksichtigung der Handelsfelle und -pelze (in German), *Zool. Jahrb. Abt. für systematik Geogr. und Biol. der Tiere* **50**, 377–450 (1925).
13. Lockte, T., "Atlas der menschlichen und tierischen Haare," (German Atlas), Leipzig, P. Schops, 1938.
14. Manby, J., Photomicrographs of Wool Fibers, New Method, *J. Text. Inst.* **21**, T231–6 (1930).
15. Mathews, J. M., "Mathews Textile Fibers," 5th Ed., New York, John Wiley & Sons, 1947, pp. 516–7.
16. McMurtrie, W., Report Upon an Examination of Wools and Other Animal Fibers, U. S. Dept. of Agriculture, Washington, D. C., 1886.
17. Mirzoeva, E. L., The Variability of Scales on Sheep Wool (in Russian), *Trud. turkmensk.-sel.-hoz. Inst.* **3**, 41–51 (1940) (English abstract in *Anim. Breed. Absts.* **10**, No. 3, 166 (1942)).
18. Reumuth, H., and Schwerdiner, H., Microscopical Study of Scale Structure of Animal Fibers, *Z. ges. Textil-Ind. (Klepzigs)* **39**, 612 (1936).
19. Saxinger, G., Eine neue Methode zur untersuchung des Haarepithels (oberhäutchens), *Z. Tierzücht. und Züchtungsbiol.* **5**, 379–88 (1925).
20. Skinkle, J. H., The Determination of Wool and Mohair by Scale Size and Diameter, *Bull. Lowell Text. Inst.*, Series 40, No. 2 (1936–37).
21. Von Bergen, W., and Mauersberger, H. R., "American Wool Handbook," 2nd Ed., New York, Textile Book Publishers, 1948.
22. Wildman, A. B., The Microscopy of Textile Fibres Aids to Their Identification, *J. Text. Inst.* **38**, T468 (1947).

Appendix

TABLE I. SCALE CHARACTERISTICS AND OUTLINE ON WOOL FIBERS

Country of origin	Type of wool	Type of fiber	Scale outline	No. of scales per in. length	No. of scales per in. length and 100 μ width	Average scale height (μ)	No. of scales along margin per 100 μ length	Thickness of the fiber (μ)	Scale index $\left(\frac{\text{scale height}}{\text{fiber thickness}}\right)$
Wild life									
U.S.	Big Horn	Undercoat	Annular	2,400	20,000	12.8	9	12.0	1.066
U.S.	Deer	Undercoat	Annular	2,800	28,000	10.1	10	10.0	1.010
U.S.	Elk	Undercoat	Annular	2,700	20,769	11.0	10	13.0	0.916
U.S.	Antelope	Undercoat	Annular	2,400	18,461	14.2	8	13.0	1.092
Fine-wool breeds									
Australia	Merino	Wool	Annular	2,250	14,062	15.3	6	16.0	0.956
U.S.	Rambouillet	Fine wool	Annular	2,400	20,000	12.2	9	12.0	1.017
U.S.	Rambouillet	Strong wool	Annular	2,200	13,750	12.0	10	16.0	0.750
Medium-wool breeds									
U.S.	Southdown	Wool	Annular	1,000	5,555	14.6	6	18.0	0.811
U.S.	Hampshire	Fine wool	Imbricate, crenate	2,600	11,818	11.4	10	22.0	0.517
U.S.	Hampshire	Coarse wool	Imbricate, crenate	2,200	7,333	13.2	8	30.0	0.440
U.S.	Shropshire	Fine wool	Annular	2,600	13,000	11.0	9	20.0	0.550
U.S.	Suffolk	Fine wool	Annular	2,400	12,000	11.6	8	20.0	0.580
U.S.	Suffolk	Coarse wool	Annular	1,800	6,000	15.6	7	30.0	0.520
U.S.	Cheviot	Fine wool	Imbricate	2,400	10,909	12.5	8	22.0	0.570
U.S.	Cheviot	Coarse wool	Imbricate	2,400	7,059	18.0	6	34.0	0.529
U.S.	Dorset Horn	Fine wool	Imbricate	2,600	10,000	13.1	9	26.0	0.504
England	Kerryhill	Fine wool	Annular	2,400	12,000	12.7	8	20.0	0.635
England	Kerryhill	Coarse wool	Imbricate	3,200	11,428	10.1	10	28.0	0.361
Long-wool breeds									
U.S.	Romney	Wool	Imbricate, crenate	2,400	8,571	13.7	6	28.0	0.489
U.S.	Lincoln	Wool	Annular	1,100	3,666	30.0	4	30.0	1.000
U.S.	Leicester	Wool	Imbricate	1,400	3,333	21.6	5	42.0	0.514
U.S.	Cotswold	Wool	Reticulate	2,700	6,750	20.5	5	40.0	0.512
England	Dartmoor	Wool	Imbricate	1,400	4,117	24.3	4	34.0	0.714
England	Wensleydale	Wool	Imbricate	1,800	6,923	22.0	4	26.0	0.846
Crossbred breeds									
U.S.	Corriedale	Fine wool	Imbricate, crenate	3,400	17,000	9.7	11	20.0	0.485
U.S.	Corriedale	Coarse wool	Imbricate, flattened	2,200	7,857	13.8	8	28.0	0.493
U.S.	Columbia	Wool	Annular	2,200	11,000	12.1	10	20.0	0.605
Mixed-wool breeds									
India	Bikaner 1	Fine wool	Annular	1,800	11,250	17.2	6.5	16.0	1.075
India	Bikaner 1	Coarse wool	Annular	1,800	12,500	18.2	6	24.0	0.758
India	Bikaner 2	Fine wool	Imbricate, crenate	2,000	12,500	16.8	6	16.0	1.050
India	Bikaner 3	Fine wool	Annular	1,900	10,611	16.8	7	18.0	0.933
India	Bikaner 4	Fine wool	Annular	1,800	9,000	16.0	5.5	20.0	0.800
India	Bikaner 5	Fine wool	Annular	1,800	10,000	18.0	6	18.0	1.000
India	Bikaner 6	Fine wool	Annular	1,900	13,571	13.2	8	14.0	0.943
India	Guferat	Fine wool	Annular	1,900	10,555	14.2	5	18.0	0.789
India	Daccan	Fine wool	Annular	2,000	16,666	13.3	8	12.0	1.108
India	Bellary	Fine wool	Annular	2,200	15,714	11.2	8	14.0	0.800
India	Nilgiri	Fine wool	Annular	2,400	12,000	12.1	8	20.0	0.605
India	Tibet	Fine wool	Annular	1,800	9,000	15.6	8	20.0	0.780
China	Sinning	Fine wool	Annular	2,200	18,333	11.7	8	12.0	0.975
China	Eastern Kansu	Fine wool	Annular	1,500	12,500	17.1	6	12.0	1.425
China	Sinho	Fine wool	Annular	1,800	12,857	13.5	7.5	14.0	0.964
China	Kokonor	Fine wool	Annular	1,700	10,625	16.2	6	16.0	1.012
China	Kansu	Fine wool	Annular	1,200	6,000	21.4	4	20.0	1.070

TABLE I—(*Continued*)

Country of origin	Type of wool	Type of fiber	Scale outline	No. of scales per in. length	No. of scales per in. length and 100 μ width	Average scale height (μ)	No. of scales along margin per 100 μ length	Thickness of the fiber (μ)	Scale index $\left(\frac{\text{scale height}}{\text{fiber thickness}}\right)$
China	Ninghsia	Fine wool	Annular	1,700	10,625	15.5	5.5	16.0	0.968
China	Suiyuan	Fine wool	Annular	1,800	13,850	14.8	6	13.0	1.057
China	Yungchang	Fine wool	Annular	2,100	15,000	12.3	7	14.0	0.879
Turkey	Akkaraman	Fine wool	Imbricate, crenate	2,400	10,909	12.4	8	22.0	0.564
Turkey	Kizil Karaman	Fine wool	Annular	2,600	13,000	13.1	8	20.0	0.655
Turkey	Kivircik	Fine wool	Annular	1,600	8,000	15.8	7	20.0	0.790
Turkey	Daglic	Fine wool	Imbricate, crenate	2,700	11,250	14.3	7	24.0	0.596
England	Blackface	Fine wool	Imbricate, crenate	2,000	10,000	13.3	7	20.0	0.665
England	Herdwick	Fine wool	Annular	1,600	8,888	18.5	6	18.0	1.028
England	Welsh Mountain	Fine wool	Imbricate, crenate	2,400	10,909	15.0	6	22.0	0.682
England	Swaledale	Fine wool	Annular	2,200	10,000	12.3	8	22.0	0.559
U.S.	Navajo	Fine wool	Annular	2,100	14,000	12.6	9	15.0	0.840
Austria	Zackel	Fine wool	Annular	1,900	13,571	14.8	7	14.0	1.057
Russia	Voloshian	Fine wool	Annular	2,200	10,714	16.0	7	14.0	1.143
Russia	Donskoi	Fine wool	Annular	2,000	14,285	14.0	7	14.0	1.000

TABLE II. SCALE OUTLINE AND CHARACTERISTICS ON HAIR FIBERS (MIXED-WOOL BREEDS)

Country of origin	Type of wool	Type of fiber	Scale outline	No. of scales per in. length	No. of scales per in. length and 100 μ width	Average scale height (μ)	No. of scales along margin per 100 μ length	Thickness of the fiber (μ)	Scale index $\left(\frac{\text{scale height}}{\text{fiber thickness}}\right)$
India	Bikaner 1	Heterotype	Reticulate	2,400	6,000	36.6	5.5	40.0	0.915
India	Bikaner 2	Hair	Imbricate, flattened	3,400	4,473	17.0	7	76.0	0.224
India	Bikaner 3	Heterotype	Reticulate, polyhedral	2,200	6,111	36.4	4	36.0	1.011
India	Bikaner 4	Heterotype	Imbricate, crenate	1,800	3,214	22.0	6	56.0	0.393
India	Bikaner 5	Hair	Reticulate, polyhedral	4,200	5,250	25.6	4	80.0	0.320
India	Bikaner 6	Heterotype	Reticulate, crenate	2,000	5,000	24.4	4.5	40.0	0.610
India	Gujerat	Hair	Imbricate, flattened	3,200	7,272	13.2	7	44.0	0.300
India	Daccan	Hair	Reticulate, polyhedral	4,600	5,750	24.5	6	80.0	0.306
India	Bellari	Hair	Imbricate, crenate	3,400	7,083	13.3	8	48.0	0.277
India	Nilgiri	Hair	Reticulate, polyhedral	2,600	7,647	12.1	6	34.0	0.356
India	Tibet	Hair	Imbricate, flattened	3,700	8,809	11.5	9	42.0	0.274
China	Sinning	Hair	Reticulare, polyhedral	3,500	3,723	39.5	3	94.0	0.420
China	Eastern Kansu	Hair	Reticulate, polyhedral	3,800	5,428	34.1	4	70.0	0.487
China	Sinho	Hair	Reticulate, polyhedral	3,600	5,806	26.0	4.5	62.0	0.419
China	Kokonor	Hair	Reticulate, polyhedral	4,800	3,750	21.8	5	128.0	0.170
China	Kansu	Hair	Reticulate, polyhedral	2,400	4,000	23.0	4.5	60.0	0.383
China	Ninghsia	Heterotype	Imbricate, crenate	1,800	4,500	25.8	4	40.0	0.645
China	Sineyuan	Hair	Reticulate, polyhedral	4,000	4,762	26.4	4	84.0	0.314
China	Yung Chang	Hair	Reticulate, polyhedral	4,000	5,000	21.2	5	50.0	0.424
Turkey	Akkaraman	Hair	Reticulate, polyhedral	4,200	6,562	17.4	6	64.0	0.272
Turkey	Kizil Karaman	Hair	Reticulate, polyhedral	4,200	8,400	14.3	5.5	50.0	0.286
Turkey	Kivircik	Hair	Reticulate, polyhedral	4,600	7,666	14.0	7.5	60.0	0.233
Turkey	Daglic	Hair	Reticulate, polyhedral	5,200	8,125	21.8	5	64.0	0.341
England	Blackface	Hair	Reticulate, polyhedral	5,400	6,750	25.3	5	80.0	0.316
England	Herdwick	Hair	Reticulate, polyhedral	2,600	5,000	22.8	5	52.0	0.438
England	Welsh Mountain	Hair	Reticulate, polyhedral	5,400	6,750	20.1	5	80.0	0.251
England	Swaledale	Hair	Imbricate, flattened	3,200	4,571	12.2	8	70.0	0.174
U.S.	Navajo	Hair	Imbricate, crenate	3,200	7,619	15.1	6	42.0	0.360
Austria	Zackel	Hair	Reticulate, polyhedral	4,100	4,881	34.3	3.5	84.0	0.408
Russia	Voloshian	Hair	Reticulate, polyhedral	4,400	6,666	35.5	2.75	66.0	0.538
Russia	Donskoi	Hair	Reticulate, polyhedral	4,800	10,285	20.1	5	46.0	0.437

TABLE III. SCALE OUTLINE AND CHARACTERISTICS ON OUTER COAT FIBERS OF WILD LIFE AND KEMP FIBERS OF MIXED-WOOL TYPES

Country of origin	Type of wool	Type of fiber	Scale outline	No. of scales per in. length	No. of scales per in. length and 100 μ width	Average scale height (μ)	No. of scales along margin per 100 μ length	Thickness of the fiber (μ)	Scale index $\left(\frac{\text{scale height}}{\text{fiber thickness}}\right)$
U.S.	Big Horn	Outer coat	Reticulate, polyhedral	6,000	2,143	27.0	5	280.0	0.096
U.S.	Deer	Outer coat	Reticulate, polyhedral	11,600	3,086	25.3	4	376.0	0.067
U.S.	Elk	Outer coat	Reticulate, polyhedral	7,600	1,969	22.3	5	386.0	0.058
U.S.	Antelope	Outer coat	Reticulate, flattened	14,000	2,661	19.3	5.5	526.0	0.037
India	Gujerat	Kemp	Imbricate, flattened	3,500	2,916	11.7	9	120.0	0.097
India	Daccan	Kemp	Imbricate, flattened	5,200	3,059	14.5	9	170.0	0.085
India	Bellari	Kemp	Imbricate, flattened	4,000	5,405	10.8	10	74.0	0.146
China	Sinning	Kemp	Imbricate, flattened	4,200	2,333	15.9	6	180.0	0.088
Turkey	Akkaraman	Kemp	Imbricate, flattened	6,200	3,100	12.8	6	200.0	0.064
Turkey	Kizil Karaman	Kemp	Imbricate, flattened	4,400	4,888	13.5	8	90.0	0.150
Turkey	Kivircik	Kemp	Imbricate, flattened	6,000	3,529	15.0	7	170.0	0.088
Turkey	Daglic	Kemp	Imbricate, flattened	6,500	6,500	10.7	9	100.0	0.107
England	Blackface	Kemp	Reticulate, honeycomb	7,200	2,727	31.1	4	264.0	0.118
England	Herdwick	Kemp	Reticulate, honeycomb	6,000	2,678	33.9	4	224.0	0.151
England	Welsh Mountain	Kemp	Reticulate, honeycomb	5,600	2,500	28.8	5	224.0	0.129
England	Swaledale	Kemp	Reticulate, honeycomb	5,800	4,328	27.7	5	134.0	0.207

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Bikaner Wool, A Leading Carpet Wool, and Its Improvement*

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Abstract

Eight samples illustrating average and extreme types of Bikaner wool were selected from 28 samples received from the Government Livestock Farm at Hissar, India. These 8 samples were analyzed for fiber types, dividing them into true wool, hair, heterotype, and kemp fibers. Both the benzol test and microscopic cross-sectional images were used in the classification. Fiber thickness, stretched fiber length, and contour ratio were determined for the 8 samples along with the surface scale measurements for the different fiber types.

AS A RESULT OF the increasing strain to keep up with the world economy and to raise the standards of living, serious efforts have been made to utilize the internal resources in most Asiatic countries. The improvement in agricultural economy has thus become of vital importance; this includes the livestock industry, which forms the backbone of agricultural countries like India and China. Closely associated with the larger class of livestock is sheep, the importance of which has been recognized since the earliest of times as a source of food and clothing.

The need for improving sheep and wool in India has attracted special attention in recent years and every effort is being made for the development of the industry. The average production of wool per sheep is reported as 1.9 lbs. a year [3], which is probably lower than that for any other sheep-raising country; the entire yearly production of 54.33 million lbs. [5] from a quality standpoint is classed as a coarse carpet wool, suitable only for the production of carpets and rough blankets. In spite of producing surplus wool, with an export figure of about 41.14 million lbs. [5] every year, the country has to import 19.24 million lbs. of apparel wools in order to meet its needs for the manufacture of clothing. The total export goes into the international trade as carpet wool. Besides the need for increasing the quantity of wool per sheep, it seems that improvement of quality, both for the production of apparel wool to meet the domestic consumption and for the development of ideal carpet wool for export, would be a befitting plan for any progressive program, with due regard to environmental and feeding conditions.

From a preliminary survey by the Marketing Department of India [3], it appears that although the foundation stock is inferior, potentialities for improvement in certain breeds are not entirely lacking. One of the promising breeds of sheep, of country-wide importance, is the Bikaner, native to the northwestern parts of India in the Rajasthan Union. It derives its name from its homeland, the Bikaner State. The breed is reported to produce one of the finest carpet wools in the world [16], and the average fleece weight is reported to be as high as 6.5 lbs. [23]. Due to the superior quality of the sheep and its wool, the breed has found favor in many other states of the country—Madras, United Provinces, Bihar, Orissa, and Assam—to replace the native inferior types or for crossbreeding. In spite of varied climates, which in many cases are too humid, with high rainfalls, as compared with its arid home-region, the breed is reported flourishing in Assam [15], Orissa [27], and Madras [6]. The breed already wields an enormous influence in Rajputana, Punjab, and United Provinces, and, with the growing interest to introduce the breed in southern and central India, Bikaner sheep and wool have become important in all regions of India. With a view to explore the possibilities and the

* This report is based on G. S. Mahal's M.S. thesis, University of Wyoming, Aug. 1949.

potentialities for improvement of this sheep and wool, 8 representative commercial samples were analyzed in the Wool Department, University of Wyoming, Laramie, Wyoming.

Position of Bikaner Wool

Bikaner wool is unique for its length, color, quality, and loftiness as a product best suited for carpets. It always commands the highest prices in the local markets as compared with other wools, which usually are double in amount by weight [4]. Because of its superior quality, the wool is mixed by the traders with inferior wools from adjoining areas and exported to foreign countries under the trade name of Vicanere wool [4]. In recent years, wool from certain localities has been so highly appreciated for its fineness and quality that certain authorities have been inclined to believe that the wool is more suitable for clothing purposes than for carpet manufacture.

A part of the wool produced is utilized by farmers in hand spinning and weaving for making articles of native dress and blankets, while a certain percentage goes into the manufacture of carpets and rugs. A major portion is exported from the home-region to markets in other parts of India for use in the mills and for foreign trade. The 3 types of wool—Magra, Chokla, and Nali—classified according to the area of production, fineness, and quality, are all mixed together before export. The wool that goes to the mills is utilized for making carpets, blankets, and woolen materials. The lofty character of the wool makes it fairly suitable for the manufacture of hosiery and blankets. Better sorts are sometimes used by the mills for tweeds.

Materials and Methods

Origin of the Wool Samples

The wool samples analyzed in this study were obtained through the courtesy of Mr. B. N. Handa, Superintendent, Government Livestock Farm, Hissar, India. In order that the samples should represent purity of the type, these were originally obtained from the Bikaner State from a dealer in the Sujanghar area who is well known for handling good quality of wool. A total of 28 samples were received. Only 8 samples representing extreme and average types in fineness and other qualities were picked by visual examination for study.

Preparation of Samples

Each sample was divided into 8 approximately equal subsamples. Great care was taken to prevent breaking of the fibers. By taking small portions from each subsample, several duplicate composite samples could be used for the study of different characteristics.

Before analysis the representative samples were scoured in order to remove extraneous matter. The method of scouring suggested by Johnston [22] was employed. Before analysis a final rinse in carbon tetrachloride was given. All burrs or other vegetable matter were carefully picked out from each sample by hand; the sample was then blended, by repeated splitting of the staples, for the study of different characteristics.

Techniques Used for Analysis

The various tests and determinations made in the analysis of the samples included: medullation test; stretched fiber length measurements: fiber thickness; contour ratio; and surface scale structure for fiber types.

Bikaner wool is of mixed type and contains different types of fibers—namely, wool, heterotype, hair, colored fibers, and kemp. Except for the colored fibers, the distinction between the fiber types is made according to the degree of medullation—no medullation (wool), partial medullation (heterotype), or complete medullation (hair). The kemp fiber is a characteristic "dead" fiber, and is comparatively thick, short, straight, and in most cases opaque white like burnt bone.

Various workers, such as Blyth [9], Roberts [29], Wilson [33], Lochner [24], Elphick [18], Darling [17], Bulgaru [12], Munz [25], and Burns, Johnston, and Chen [14], conducted analyses of mixed wools; their basic procedure was to determine the proportion of different types of fibers, although using slightly different names in some instances. This is important because all the fibers possess variable physical properties, and a change in their proportion is likely to alter the character and nature of a wool. The method for the analysis of mixed wools has now been adopted universally. Although the analysis of fiber types is a useful guide in evaluating the quality of mixed wools from a manufacturing viewpoint, it does not give the actual amount of medullation in a sample due to varying amounts of medullated and non-medullated portions in the

heterotypes. This estimation is essential for a critical selection of sheep in any breeding-improvement program. Accordingly, the medullation test was carried out under two different techniques—fiber-count analysis, and cross-sectional medullation test.

For a counting analysis, duplicate composite samples were separated into the different types of fibers by using Elphick's benzol test. However, it was found necessary for efficient results that benzol, with a refractive index of 1.50, be employed. In case of doubt, a microscope was employed for the identification of the fibers. A white paper background was used to identify colored fibers. Fibers in each class were counted and their proportions worked out mathematically.

For the cross-sectional medullation test, duplicate composite samples were used for each type of wool. Hardy's technique [19] was used in making cross sections. Three sections were made of each sample —namely, one at the base, one at the middle, and one at the tip. These sections were projected, using 500× magnification, on a white surface of 25 cm. × 10 cm. area, and the number of medullated and non-medullated fibers were counted and recorded. The total number of medullated and non-medullated fibers in the different samples were determined. From these figures the percentages of the two fiber types were calculated.

Stretched fiber length measurements were made of the fiber types which were separated out in the count analysis. Burns' improved technique [13] was used for the measurements. One hundred fibers of each type were measured, except when their total number in the sample was smaller.

Thickness measurements of each sample as a unit and of the fiber types after separation were made separately. Duplicate composite samples were used in the former case, while the fiber types that were used for the stretched fiber length measurements were utilized in the latter case. The longitudinal short-section method was used in the thickness measurements [1]. The minimum number of readings to come within a prescribed limit of error was first worked out by the formula employed by Roberts [28], and all measurements were made accordingly. Only 100 readings were recorded to measure the fiber types.

The contour ratio, which expresses the ellipticity of the fiber cross section, was measured in terms of the ratio of the major to the minor axis [31]. Barker [8] has proved that in two wools of the same fineness, the more circular wool spins better. Hardy's technique [19] was used in making the cross sections. The cross-sectional fiber images were projected and photographed on sensitized bromide paper.

The major and minor axes of each fiber cross section were measured with the bi-diameter scale and recorded. The contour ratio was worked out from these readings.

The study of scale structure was made by obtaining surface impressions with the aid of a thermoplastic film according to the technique developed by Hardy and Plitt [20]. Until recent years, an efficient method for the study of scale structure had been a difficult problem, but the above method gives satisfactory results. The impressions on the film were mounted on a glass slide and projected at a magnification of 500 diameters. Photographs of projected images were then obtained on sensitized paper, showing representative fibers for the different measurements.

The attributes studied were the scale outline, the number of scales per unit length, the average visible scale height, the number of scales along the margin per 100μ length, and the relationship of scale height to fiber diameter.

Results and Discussion

Medullation Test

The results of medullation test both by fiber-type analysis and cross-sectional technique are presented in Table I. The fiber-count analysis reveals that the average fiber-type content in the 8 samples is 58.6% true wool, 29.8% heterotype, 11.4% hair, and 0.1% kemp. The largest variation is in the true wool fibers—from 16.8% to 96.5%; variation in the heterotypical fibers is from 3.5% to 49.3%, and in hair from 11.3% to 33.6%. Four samples show total freedom from hair and 6 samples are free from kemp. The average content of kemp fiber is only 0.1%, which may be considered negligible. No colored fibers were found in any of the 8 samples.

By the cross-sectional image method, the average percentage of non-medullated fibers is 70.7%, and of medullated fibers 29.3%. The range of variation is from 23.8% to 98.9% in the former case, and from 1.1% to 76.2% in the latter.

From both of the above tests it is evident that

TABLE I. RESULTS OF MEDULLATION TEST

Sample No.	Percentage of fiber types by count: True wool	Hetero-type	Hair	Kemp	Percentage of total fibers by cross-section image: Non-medullated	Medullated
1	57.8	41.9	—	0.3	91.4	8.6
2	39.4	49.3	11.3	—	54.1	45.9
3	38.9	39.9	21.2	—	51.4	48.6
4	96.5	3.5	—	—	98.9	1.1
5	16.8	49.1	33.6	0.5	23.8	76.2
6	94.6	5.4	—	—	98.1	1.9
7	80.7	19.3	—	—	95.8	4.2
8	44.6	30.1	25.3	—	52.4	47.6
Average	58.6	29.8	11.4	0.1	70.7	29.3

there is a wide range of variation in the true wool fibers of the samples. In samples Nos. 4 and 6 the true wool content approaches very near to total freedom from medullation. According to various workers, such as Bryant [11], Barker [8], Elphick [18], Waters [32], and Nanda, Singh, and Mogre [26], medullation in wool is probably inherited. The results thus show high potentialities for total elimination of medullation in the breed and for the evolution of a true wool type of sheep by selective breeding. Townend and McMahon [30], by subjecting large quantities of Romney wool to various stages of manufacture, noticed that hairiness up to the extent of 6%, as determined by McMahon's Medullometer, did not affect the processing properties of the wool and produced no marked difference in the appearance and handle of either woven or knitted fabrics. The hairiness could not be detected in dyed cloths. An extremely low medullation content in samples Nos. 4, 6, and 7 shows that suitable sorts can be picked up from the Bikaner wool which are suitable for the manufacture of clothing material.

Stretched Fiber Length Measurements

The stretched length measurements of the different fiber types and the percentages of variation are shown in Table II.

The range of average length in the true wool fibers is from 6.25 cm. to 14.33 cm., with a coefficient of variability range of from 7.8% to 26.2%. The average length of 800 fibers in all samples was 10.38 cm., with a coefficient of variability of 31.0%.

TABLE II. STRETCHED FIBER LENGTH MEASUREMENTS OF FIBER TYPES

Sample No.	True wool: Mean (cm.)	Coefficient of variability (%)	Heterotype: Mean (cm.)	Coefficient of variability (%)	Hair: Mean (cm.)	Coefficient of variability (%)
1	10.24	12.2	18.17	14.7	—	—
2	9.07	10.7	13.47	12.6	10.16	7.8
3	8.28	14.6	14.47	11.2	—	—
4	14.33	18.0	17.58	17.3	15.21	10.5
5	6.25	15.4	9.81	16.1	13.31	12.9
6	13.87	26.2	17.08	15.9	—	—
7	10.39	18.3	13.60	12.1	—	—
8	10.57	7.8	13.05	14.3	14.77	10.4

The range of average length in the heterotypical fibers is from 9.81 cm. to 18.17 cm., with a coefficient of variability range of from 11.2% to 16.1%. The average length of 714 fibers in all samples was 14.34 cm., with a coefficient of variability of 23.1%.

The range of average length in the 4 samples for hair fibers is from 10.16 cm. to 15.21 cm., with a coefficient of variability range of from 7.8% to 12.9%. The average length of 400 fibers in all samples as a whole was 13.21 cm., with a coefficient of variability of 20.7%.

Although there is good uniformity in the fiber types of individual samples, the variability is larger if the samples are taken as a whole. The highest variability is noticeable in the true wool fibers, and the lowest in the hair fibers. If the hair and heterotypical fibers were eliminated through selective breeding, there would be ample scope to improve the length of the wool.

Fiber Thickness Measurements

The thickness measurements of the entire samples and of the fiber types, with the variabilities, are given in Table III.

The average range in the thickness measurements of 8 samples is from 26.55μ to 47.23μ, with a coefficient of variability range of from 32.1% to 59.2%. The average fiber diameter of 8 samples as a whole is 34.68μ. The minimum measurement was 12.5μ for a true wool fiber, and the maximum was 117.5μ for a hair fiber.

The range of average thickness for the true wool fibers in the 8 samples is from 16.45μ to 31.00μ, with a coefficient of variability range of from 3.8%

TABLE III. THICKNESS MEASUREMENTS OF ENTIRE SAMPLES AND OF THE FIBER TYPES

Sample No.	Entire sample		True wool		Heterotype		Hair	
	Mean (μ)	Coefficient of variability (%)	Mean (μ)	Coefficient of variability (%)	Mean (μ)	Coefficient of variability (%)	Mean (μ)	Coefficient of variability (%)
1	26.77	49.2	16.45	18.6	33.80	29.9	—	—
2	34.80	43.3	23.83	16.8	32.65	19.9	55.45	29.5
3	34.66	36.2	22.63	12.9	31.60	20.3	—	—
4	27.56	32.1	25.52	30.5	49.62	36.8	45.65	15.3
5	46.67	59.2	19.85	3.8	30.80	24.8	71.62	25.5
6	26.55	34.2	25.70	35.9	44.80	18.7	—	—
7	33.18	32.2	28.12	25.6	49.10	14.3	—	—
8	47.23	42.8	31.00	17.8	40.45	20.8	17.68	25.2

to 35.9%. The average thickness of 800 fibers in all samples was 24.16μ, with a coefficient of variability of 29.9%.

The range of average thickness for heterotypical fibers in all samples is from 30.80μ to 49.62μ, with a coefficient of variability range of from 14.3% to 36.8%. The average thickness of 800 fibers in the 8 samples as a whole was 37.74μ, with a coefficient of variation of 26.8%.

The range of average thickness for hair fibers in the 4 samples is from 45.65μ to 71.62μ, with a coefficient of variation range of from 15.3% to 29.5%. The average thickness of 400 fibers in the 4 samples was 63.56μ, with a coefficient of variation of 33.4%.

The thickness measurements show a high variation both in the entire samples measured individually and in the fiber types. The finest samples, with thicknesses of 26.55μ and 26.77μ, show variations of 34.2% and 49.2%. The greatest uniformity is evident in the true wool fibers, whereas the hair fibers are the most variable. Barker [7], in his report on the Shantung and Woozie sheep of China, does not favor a variation higher than 25% in wools to be used for clothing material. In the present study the variation is higher than 25% both in the entire samples and in the fiber types. For an intended improvement of wool as a whole, it appears that the greatest emphasis should be on attaining uniformity of fineness of fibers. The wide range of variation in the true wool of from 3.8% to 35.9% indicates high potentialities to achieve this objective.

The amount of medullation and the thickness measurements of different samples apparently show a direct relation to one another. The thickness increases with increase of medullation in the sample. But, even with such increases, hair fibers with a thickness of 30μ and wool fibers with a thickness of 50μ are also encountered, which evidently shows that thickness alone does not control medullation in wool; some other factor, probably genetic, is partly, if not entirely, responsible.

Contour-Ratio Measurements

The contour-ratio measurements in the 8 samples are shown in Table IV.

The average contour ratio in the 8 samples is 1.284, with a range of from 1.170 to 1.382. According to trade opinion, the spinning properties of wool can be divided into 3 groups [31]—*i.e.*, very good spinning, with a contour ratio of below 1.2; average spinning, with a contour ratio of from 1.2 to 1.22; and fair spinning, with a contour ratio above 1.22. The results thus show that although considered as a whole, the wool samples show fair spinning property—1 of the samples possesses very good, 1 medium, and 6 fair spinnability. The potentialities for a very good spinning property, however, are evident.

The contour ratio seems to be related to the percentage medullation in the different samples. With increase of medullation there is an increase in contour ratio and a poorer spinning property. This is

TABLE IV. CONTOUR-RATIO MEASUREMENTS IN THE DIFFERENT SAMPLES

Sample No.	Average contour ratio	No. of fibers measured
1	1.282	104
2	1.300	101
3	1.355	100
4	1.226	130
5	1.373	120
6	1.170	160
7	1.256	130
8	1.382	180

further proof to the general assumption that increase in medullation lowers the spinning property of wool.

Surface Scale Structure on Fiber Types

The various characteristics of the scale structure of the fiber types in the different samples are shown in Table V.

The average number of scales on true wool fibers per in. length is 1,900, with a range of from 1,700 to 2,300; and on heterotypical and hair fibers is 2,788, with a range of from 1,800 to 3,400. When calculated on the basis of 100μ width and the same length, the average number is 10,797, with a range of from 9,000 to 13,571, in the former case; and 5,332, with a range of from 3,214 to 7,750, in the latter. The average scale height is 16.7μ on the true wool fibers and 26.4μ on heterotypical and hair fibers.

Although the number of scales per unit length on the heterotypical and hair fibers seems larger than that on the true wool fibers, it is half as much when compared on the equal basis of the thickness of the fiber.

The number of scales along the margin per 100μ length of fiber was also worked out in the fiber types. The average for the true wool fibers was 6.4, with a range of from 5½ to 8; that for the heterotype and hair fibers was 5, with a range of from 4 to 7.

A relationship of scale height to fiber thickness, designated as the "Scale Index" by Hausman [21], was also calculated for fiber types in individual samples. The average figure for the fiber types was 0.972 for wool, 0.687 for heterotypes, and 0.464 for hair fibers. It appears that as the diameter of the fiber increases there is a decrease in the "Scale Index."

The shape of the scales on the true wool fibers was of annular or coronal form (single scale along the width of the fiber), as described by Blyth [10], and resembled the segments of a young bamboo cane. In the case of heterotypical and hair fibers, the shape of the scales was polygonal or flattened. Various forms of pentagonal and hexagonal shapes were seen. It was apparent that with a smaller thickness the shape of the scales was more or less of a columnar type, but it inclined to become rectangular and flattened with increase in the thickness of the fiber.

TABLE V. RESULTS OF THE SURFACE SCALE STRUCTURE OF FIBER TYPES

Sample No.	No. of scales per in. length		No. of scales per in. length and 100 μ width		Average scale height (μ)	
	True wool	Hair or hetero-type	True wool	Hair or hetero-type	True wool	Hair or hetero-type
1	2,300	2,400*	11,250	6,000*	17.2	36.6*
2	2,000	3,400†	12,500	4,473†	16.8	17.0†
3	1,900	2,200†	10,611	6,111†	16.8	36.4†
4	1,800	1,800*	9,000	3,214*	16.0	22.4*
5	1,800	4,200†	10,000	5,250†	18.0	25.6†
6	1,900	2,000*	13,571	3,000*	13.2	24.4*
7	1,800	3,000*	10,000	7,750*	18.0	29.0*
8	1,700	3,200†	9,444	4,848†	17.6	20.0†
Average	1,900	2,788	10,797	5,332	16.7	26.4

* Heterotypical fibers.
† Hair fibers.

Conclusions

The following conclusions are evident from the results obtained from this study:

1. The results of the count analysis of fiber types and their dimensional characteristics in the 8 samples as a whole show that the wool is very near to the carpet wool standards as worked out by Burns, Johnston, and Chen [14] and the Southwestern Sheep Breeding Laboratory at Fort Wingate, New Mexico, from their work on Navajo Sheep [2]. However, it appears that the variation in the length and fineness of fiber types is slightly larger—by 4% to 5%. The average thickness of the heterotypical fiber is 7μ greater than desirable. The Bikaner wool as a commercial type can therefore be considered as very good for carpet and rug manufacture, although some improvement in attaining uniformity of fiber thickness is necessary in order to fix it as an ideal carpet type of wool. Individual samples Nos. 4 and 6, with high true wool contents of 96.5% and 94.6%, respectively, seem too good for ideal carpet wool; Nos. 5 and 8 with true wool contents of 16.8% and 44.6%, respectively, appear rather poor in this respect. Samples Nos. 1 and 7 are very close to the required standard, and Nos. 2 and 3 are slightly poorer for this purpose.

2. If the average proportion of fiber types is considered to be very near to ideal carpet wool by count analysis, the cross-section medullation test of the same samples reveals that by this method an ideal carpet wool should show 75% non-medullated fibers and should not exceed a limit of 80%.

3. Although the average quality of the samples reveals that the wool in a mixed form is best suited for carpets, the extremely low amounts of medullation in certain individual samples show that selected sorts can be utilized for the manufacture of clothing material. The wide range of medullated fibers in the different samples indicate further that there are high potentialities for evolving an apparel-wool type of sheep by selective breeding. It is highly desirable to eliminate kemp entirely from the fleece.

4. The analysis of medullation in the individual samples indicates that there are great possibilities for improving the wool for apparel fabrics, the variation in the fiber thickness being rather large to require particular attention. Even the finest samples, with average thicknesses of 26.55μ and 26.77μ, show variations of 34.2% and 49.2%. For any program of improvement, therefore, the greatest emphasis should be to attain the uniformity of fibers. The uniformity in the case of true wool fibers is fairly satisfactory.

5. The stretched fiber length of different types of fibers in the individual samples do not show any marked elongation of the outer coat compared to the inner coat as seen in most of the poor carpet wools. This characteristic is highly desirable for the spinning value of carpet wools.

6. There appears to be a relationship between the amount of medullation and the thickness of the entire sample, the diameter increasing with increased medullation in the sample. However, hair fibers with a diameter of 30μ and wool fibers with a diameter of 50μ show that the diameter alone does not control medullation in wool, and some other factor, probably genetic, is partly, if not entirely, responsible.

7. The average contour ratio of the 8 samples is 1.284, designating a fair spinnability according to the trade opinion. One of the samples showed a very good spinnability, with a contour of 1.179, and one showed a medium spinnability. This again reflects possibilities for improvement. Higher contour ratio seems to be related to higher amount of medullation in the individual samples.

8. The average number of scales on true wool fibers with an average thickness of 17.2μ is 1,900 along one surface, which is very close to that for the fine wool Merino. When compared on the equal basis of unit length and 100μ width, the number of scales on the true wool fibers was double that found on the heterotypical or hair fibers. The outline of the scales is uniform, regular, and annular on the true wool fiber, but is irregular, with pentagonal, hexagonal and rectangular forms, on the hair and heterotypical fibers.

9. For a mass improvement of Bikaner sheep it seems necessary that only tested rams be used for breeding which show a desirable amount of medullation in the fleece and possess maximum uniformity in fiber thickness.

Literature Cited

1. American Society for Testing Materials, Standards on Textile Materials, D419–477, 1947.
2. Anon., Annual Report of the Southwestern Range and Sheep Breeding Laboratory, Fort Wingate, New Mexico, 1940.
3. Anon., "Handbook on the Quality of Indian Wools," Agr. Marketing Adviser to Govt. of India, Indian Market Series No. 33, 1942.
4. Anon., "Report on the Marketing of Wool and Hair in India," Central Agr. Marketing Dept., Govt. of India, Marketing Series No. 54, 1945, pp. 1–141.
5. Anon., "Brochure on the Marketing of Wool in India," Agr. Marketing Adviser to Govt. of India, Brochure Series No. 2, 1948, pp. 3–4.
6. Baghavachari, K. V., Poultry and Sheep Development at the Livestock Research Station, Hosur (Madras), *Indian Farming* **6**, 584–5 (1945).
7. Barker, A. F., "Report on Shungteh and Wushing Sheep and Wool Based Upon a Visit to the Sheep Exhibition at Chungteh, Shanghai, Chiao-Tung," Univ. Research Inst. Bull. No. 9, 1937.
8. Barker, S. G., "Wool Quality," London, His Majesty's Stationery Office, 1931.
9. Blyth, J. S. S., Micrological Analysis of Two Fleeces from Black Face Sheep, *Ann. Applied Biol.* **10**, 301–11 (1923).
10. Blyth, J. S. S., Studies on the Fleece Fibers of British Breeds of Sheep (in English), *Z. Tierzücht. und Züchtungsbiol.* **7**, 3 (1926).
11. Bryant, D. M., A Note on the Inheritance of Kemp in Black Face Sheep, *J. Text. Inst.* **7**, T585–7 (1933).
12. Bulgaru, I., A Morphological Study of the Wool of the White Turcana Sheep (in French), *Ann. Inst. Natl. Zootech. Rouman* **4**, 277–93 (1935) (Abstract in *Anim. Breed. Absts.* **4**, 188 (1935)).
13. Burns, R. H., Monthly Wool Growth of Rambouillet Ewes, *J. Text. Inst.* **22**, T100–1 (1940).
14. Burns, R. H., Johnston, A., and Chen, W. C., The Improvement of Chinese and Other Carpet Wools, *J. Text. Inst.* **31**, T37–48 (1940).
15. Chakrabarti, S., Assam, Upper Shillong Farm, *Indian Farming* **3**, 290–1 (1942).
16. Chen, W. C., "Analysis and Comparison of Chinese and Other Carpet Wools," M.S. Thesis, University of Wyoming, 1939; *cf.* reference [14].

17. Darling, F. F., Studies on the Biology of the Fleece of the Scottish Mountain Black Face Breed of Sheep (in English), *Z. Zücht. und Züchtungsbiol.* **B24**, 3, 329 (1932).
18. Elphick, B. L., The Detection and Estimation of Medullated Fibers in the N. Z. Romney Fleeces, *J. Text. Inst.* **23**, T367–85 (1932).
19. Hardy, J. I., "A Practical Method for Making Thin Cross Sections of Fibers," U. S. Dept. of Agriculture, Circ. No. 378, 1935.
20. Hardy, J. I., and Plitt, M., "An Improved Method for Revealing the Surface Structure of Fur Fibers," Wild Life Circ. No. 7, U. S. Department of Interior, 1940.
21. Hausman, L. A., Recent Studies of Hair Structure Relationship, *Sci. Monthly* **30**, 258–77 (1930).
22. Johnston, A., A Quick Method of Scouring Small Samples of Wool, *Pastoral Rev.* **44**, No. 5, 6 (1934).
23. Kaura, R. L., Some Common Breeds of Indian Sheep, Parts I and II, *Indian Farming* **2**, No. 4, 175 (1941); **3**, No. 3, 122 (1942).
24. Lochner, J. S., "A Biological and Statistical Study of the Development of the Fleece of the Scottish Mountain Blackface Breed of Sheep from Birth to Maturity," Ph.D. Thesis, Edinburgh University, 1931.
25. Munz, H., "Observations on Some Wool Samples from North Eastern Asia," Commonwealth of Australia, Council of Scientific and Industrial Research, Pamphlet No. 69, 1937.
26. Nanda, P. N., Singh, G., and Mogre, S. B., A Rapid Field Method of Estimating Medullation in Wool and A Plan for Improvement of Village Flocks, *Indian Farming* **7**, 585 (1945).
27. Patnaik, U., Establishment of Sheep Breeding Units in Orissa, *Indian Farming* **5**, 65–6 (1944).
28. Roberts, J. A. F., Fleece Analysis for Biological and Agricultural Purposes, *J. Text. Inst.* **21**, T127–64, A405 (1930).
29. Roberts, J. A. F., "Kemp in the Fleeces of Welsh Mountain Sheep," Ext. from Pub. No. 59 of Brit. Assoc. of Woolen and Worsted Industries, 1926.
30. Townend, S., and McMahon, P. R., Significance of Hairiness to the Wool Textile Industry, Ext. from *New Zealand J. Sci. Technol.* **26**, No. 1, 1–20 (1944).
31. Von Bergen, W., and Mauersberger, H. R., "American Wool Handbook," 2nd Ed., New York, Textile Book Publishers, 1948.
32. Waters, R., "First Annual Report of Fleece Testing Section," Massey Agr. College, New Zealand, Bull. No. 4, 1935.
33. Wilson, J. F., A Macroscopical Analysis of the Fleeces of Four Romney Rams, *Hilgardia* **3**, No. 19, 584–99 (1929).

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INDUSTRIAL SECTION

Effect of Construction on the Laundering Shrinkage of Knitted Woolens*

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IN THE FABRICATION of knitted garments, it is well known that the tightness of the structure affects the laundering behavior in use. Furthermore, it is generally understood in the industry and by most consumers that a loose, fluffy lady's sweater, for example, must be handled more carefully than a pair of machine-knit socks. While the pioneering work of Dutton [3] has provided the first quantitative approach to the role of knitting stiffness in shrinkage, the factors constituting "tightness of structure" are not yet precisely understood.

Further work in this field was prompted by the recognition by the Army Quartermaster Corps that replacement of wool service clothing was largely due to shrinkage in washing under field and other conditions. While antifelting treatments have contributed greatly to the amelioration of this problem, it is becoming clear that specification of the use of shrink-resistant wool, in the absence of construction limits, provides only a partial solution to the problem. It was, therefore, with the practical goal of providing a basis for the modification of procurement specifications with respect to construction that this investigation was undertaken, in the hope that improvement in laundering stability might be achieved and that some insight into the quantitative factors contributing to it might be gained.

Materials and Methods

Materials

Six-hundred lbs. of 64's grade Australian wool top was obtained and divided into four parts. One part was set aside, and the others were treated in the mill by a commercial, continuous top-treating process employing alkaline wet chlorination [5]. The treatment used was at three different levels, as judged by the top-shrinkage test [1]; the latter measures the length change of top specimens subjected to wet mechanical action, and over a long period of use has been shown to correlate well with the shrinkage behavior of garments made from the top. The top-shrinkage values for the four groups of top were: untreated—35% to 40%; "mild" treatment—15%; "optimum" treatment—7%; "severe" treatment—2%. The adjectives describing the level of chlorination are based on the experience of processors in relating top-shrinkage values to the performance of Army fabrics; a 7% to 12% top shrinkage is considered "optimum" for most Army constructions; a 12% to 20% top shrinkage, while adequate for many civilian consumer applications, may be too mild for vigorous Army laundering methods, while a 2% to 7% top shrinkage generally indicates a more severe treatment than is required for most uses.

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The wool was top-dyed with chrome colors and then spun into the following yarns:

1—15/1 Bradford, normal knitting twist
2—15/1 Bradford, higher than normal twist
3—15/2 Bradford, normal knitting twist
4—15/2 Bradford, higher than normal twist in singles
5—26/1 Bradford, normal knitting twist
6—26/1 French, normal knitting twist
7—26/2 Bradford, normal knitting twist
8—26/2 French, normal knitting twist
9—36/1 French, normal knitting twist
10—36/2 French, normal knitting twist

The spinner's judgment as to "normal" or "higher than normal" twists was followed; actual values of the twists in the yarns are presented below.

The yarns, now representing ten types at four levels of treatment, were fabricated into socks or tubing on commercial-scale knitting machines, using either flat or 1 × 1 rib stitches. For each knitting machine, that number of loops was used which would produce a commercially acceptable fabric with a given type of yarn. The knitting stiffness was varied above and below this value in order to give a tight and a loose or sleazy construction in addition to the normal texture.

Methods

The knit fabrics were relaxed by submerging them in water at 80°F for 2 hrs., followed by hydro-extraction and tumble drying.

The laundering procedure used for most of the data reported here was similar to that known as the Army-wool mobile laundering, except that the load used was increased from 20 lbs. to 23½ lbs. in order to accommodate all of the specimens in a single run. The wash cycle comprised two 5-min. suds, using Igepon T as detergent, followed by three 3-min. rinses, extraction, and tumble drying; water temperature was maintained at 100°F. Five wash cycles resulted in severe felting of most of the untreated fabrics.

In order to resolve differences in felting behavior of some of the treated samples, a milder laundering procedure was also used in some cases. This comprised a 4-min. suds followed by two 2-min. rinses at high water level. This latter test is referred to below as the mild laundering. Measurements were made after 5, 10, and 20 mild launderings of this type.

Results and Discussion

In view of the large number of data obtained, the effect of each factor of construction is isolated, where possible, and the results are presented in separate tables. While the results for a given sample may thus be given in several places, it is believed that this method of presentation is justified because it greatly facilitates comparison.

Effect of Knitting Stiffness

For any given yarn, the tightness of knit or density of the fabric appears to be the most important variable of construction from the point of view of effect on felting shrinkage. Data illustrating the effect of this factor on untreated wool are presented in Table I. As shown by these results, the tighter

TABLE I. LAUNDERING SHRINKAGE OF UNTREATED KNITTED FABRICS AS A FUNCTION OF KNITTING STIFFNESS

Fabric	Yarn No.	Fabric texture (wales/ in.)	Fabric texture (courses/ in.)	Shrinkage in 5 Army mobile launderings Wales* (%)	Shrinkage in 5 Army mobile launderings Courses† (%)
Flat-knit tubing	15/1	19	22	24	15
	15/1	20	25	22	11
Flat-knit tubing	15/2	13	16	24	14
	15/2	14	18	20	11
Rib-knit tubing	15/2	8	13	32	12
	15/2	12	18	14	0
Flat-knit tubing	26/1	25	28	24	13
	26/1	27	33	16	8
Flat-knit socks	26/2	17	20	28	19
	26/2	18	22	24	14
Flat-knit tubing	26/2	11	13	46	38
	26/2	14	20	35	26
Rib-knit tubing	26/2	11	17	35	25
	26/2	15	23	21	11
Flat-knit tubing	36/1	25	30	33	24
	36/1	30	46	12	6
Rib-knit tubing	36/1	22	27	21	21
	36/1	22	36	11	11
Flat-knit tubing	36/2	18	23	29	19
	36/2	20	26	22	13

* By wales shrinkage is meant shrinkage in the length dimension.

† By courses shrinkage is meant shrinkage in the width dimension.

TABLE II. LAUNDERING SHRINKAGE OF KNITTED FABRICS MADE FROM CHLORINATED WOOL AS A FUNCTION OF KNITTING STIFFNESS

Fabric	Yarn No.	Level of treatment	Fabric texture (wales/in.)	Fabric texture (courses/in.)	Shrinkage in 5 Army mobile launderings: Wales (%)	Shrinkage in 5 Army mobile launderings: Courses (%)
Rib-knit tubing	15/1	Optimum	13	18	13	8
	15/1	Optimum	16	20	10	8
Flat-knit tubing	15/1	Optimum	20	20	11	6
	15/1	Optimum	21	24	7	2
Flat-knit tubing	15/2	Optimum	7	8	34	8
	15/2	Optimum	8	10	21	12
			11	14	14	9
Flat-knit tubing	15/2	Severe	6	8	10	3
	15/2	Severe	8	10	1	2
Rib-knit tubing	15/2	Optimum	7	13	16	−4
	15/2	Optimum	13	18	7	−4
Rib-knit tubing	26/2	Optimum	11	18	17	5
	26/2	Optimum	14	23	9	3
Rib-knit tubing	26/2	Severe	11	17	6	−4
	26/2	Severe	13	19	1	−5
Flat-knit tubing	26/2	Optimum	10	12	19	6
	26/2	Optimum	14	17	10	1
Flat-knit tubing	26/2	Severe	10	13	10	−1
	26/2	Severe	14	18	4	2

construction resists felting to a greater extent than does the slack knit made with the identical yarn. By increasing the knitting stiffness to a fairly high level, a substantial improvement in fabric stability is attained.

That the effect of knitting stiffness is not limited to untreated wool can be seen from the data in Table II, in which are summarized results of laundering shrinkage measurements on treated wool fabrics. The decrease in feltability with increasing knitting stiffness is again noted, this result showing good general agreement with the conclusions of Dutton on the role of knitted fabric texture in shrinkage [3, 4]. The results in Table II indicate that the manufacture of a satisfactory shrink-resistant garment depends upon a judicious combination of a proper level of treatment with a sufficiently firm construction. Thus, while a shrink-resistant garment can be made from untreated yarns knitted extremely tightly, such a garment would suffer a loss of the desirable softness and extensibility which are among wool's chief virtues. Conversely, a sleazy construction can be made quite shrink-resistant by overtreatment, but only with a resulting loss of soft hand and good wearing qualities.

Effect of Yarn Twist

The shrinkage in laundering of untreated fabrics in which the yarns differed in twist is shown in Table III. Since the previous section has confirmed the importance of knitting stiffness, comparisons are made only between fabrics which are similar in this respect.

The results indicate a small but consistent trend towards lower shrinkage values for the fabrics made with the higher-twist yarns. It is to be noted that the singles yarns differed in twist to a rather minor degree, and the differences in the felting of fabrics knitted from the 15/1 yarns, for example, are quite small.

Similar data are presented in Table IV for the fabrics knitted from shrink-resistant wool, in which similar small improvements in felt-resistance accompany the use of higher-twist yarns. It is observed that the improvement tends to be greater

TABLE III. LAUNDERING SHRINKAGE OF KNITTED FABRICS MADE FROM UNTREATED WOOL AS A FUNCTION OF YARN TWIST

Fabric	Yarn No.	Fabric texture (wales/in.)	Fabric texture (courses/in.)	Yarn twist Singles (t.p.i.)	Yarn twist Ply (t.p.i.)	Shrinkage in 5 Army mobile launderings Wales (%)	Shrinkage in 5 Army mobile launderings Courses (%)
Flat-knit tubing	15/1	19	24	6.7	—	23	13
	15/1	19	24	8.1	—	20	11
Rib-knit tubing	15/1	14	18	6.7	—	28	18
	15/1	14	18	8.1	—	27	18
Flat-knit tubing	15/2	14	17	3.9	7.0	26	17
	15/2	14	17	7.7	5.1	23	13
	15/2	7	10	3.9	7.0	52	39
	15/2	7	9	7.7	5.1	47	33
	15/2	11	16	3.9	7.0	33	25
	15/2	11	15	7.7	5.1	34	25
Rib-knit tubing	15/2	8	13	3.9	7.0	39	15
	15/2	8	13	7.7	5.1	32	12
	15/2	10	13	3.9	7.0	33	10
	15/2	9	15	7.7	5.1	30	7

TABLE IV. LAUNDERING SHRINKAGE OF KNITTED FABRICS MADE FROM SHRINK-RESISTANT WOOL AS A FUNCTION OF YARN TWIST

Fabric	Yarn No.	Level of treatment	Fabric texture (wales/in.)	Fabric texture (courses/in.)	Yarn twist Singles (t.p.i.)	Yarn twist Ply (t.p.i.)	Shrinkage in 5 Army mobile launderings Wales (%)	Shrinkage in 5 Army mobile launderings Courses (%)
Flat-knit socks	15/1	Optimum	20	24	6.7	—	10	5
	15/1	Optimum	20	24	8.1	—	8	4
Flat-knit socks	15/2	Optimum	13	16	3.9	7.0	12	4
	15/2	Optimum	13	16	7.7	5.1	9	4
	15/2	Optimum	14	17	3.9	7.0	10	4
	15/2	Optimum	14	17	7.7	5.1	9	2
	15/2	Optimum	7	8	3.9	7.0	34	−8
	15/2	Optimum	6	8	7.7	5.1	22	3
Flat-knit socks	15/2	Severe	6	8	3.9	7.0	10	−3
	15/2	Severe	7	7	7.7	5.1	7	−2

for the slacker-knit fabrics, an effect which can also be seen from some of Dutton's results [4].

Effect of Plying of Yarns

The role of plying in felting behavior was studied by laundering knitted fabrics made from 15's single ply yarns and comparing the results with those for fabrics made from 26's and 36's, 2-ply. Such fabrics of similar texture were considered to be substantially the same with respect to weight. The results of wash tests are given in Table V for both untreated wool and for top subjected to the "optimum" chlorination treatment.

Plying is seen to produce no effect on the laundering shrinkage of untreated fabrics. On the other hand, the data in Table V suggest that with shrink-resistant wool, plying may result in superior resistance to felting. This is, however, believed to result from the differences in yarn twist in the samples that were available for comparison. The singles twist of the 15's, 26's, and 36's yarns used in the treated fabrics were, respectively, 8.2, 8.8, and 11.6 turns per inch. The felting of the samples made from the 26/2 yarn is similar to that knit from the 15/1 yarn, whereas the felting of the 36/2 yarn with higher twist is lower. The decrease in felting observed with the 36/2 higher-twist yarn is

TABLE V. SHRINKAGE OF KNITTED FABRICS AS A FUNCTION OF PLYING OF YARNS

Fabric	Yarn No.	Fabric texture (wales/in.)	Fabric texture (courses/in.)	Shrinkage in 5 Army mobile launderings: Wales (%)	Shrinkage in 5 Army mobile launderings: Courses (%)
Flat knit Untreated	15/1	20	25	22	12
Flat knit Untreated	36/2	20	26	22	13
Flat knit Untreated	15/1	19	22	28	14
Flat knit Untreated	26/2	18	22	25	14
Flat knit Untreated	36/2	18	23	29	19
Flat knit Optimum treatment	15/1	20	24	8	4
Flat knit Optimum treatment	36/2	20	24	3	3
Flat knit Optimum treatment	15/1	20	20	11	6
Flat knit Optimum treatment	26/2	18	21	9	8
Flat knit Optimum treatment	36/2	19	22	3	3

similar to that given in Table IV, and may therefore be attributed to the twist rather than to the plying. It is concluded that plying has little effect on felting in the absence of other interactions.

Type of Spinning

Comparisons for feltability of untreated fabrics made from yarns which were spun on the French or on the Bradford system are shown in Table VI. The results indicate negligible difference in felting behavior.

Effect of Yarn Number

It was considered of interest to compare the fabrics of as nearly identical texture as possible but made from different untreated yarns. This, in effect, constitutes a different way of changing the weight of the cloth than through varying the knitting stiffness. The comparisons are shown in Table VII.

The results indicate that the heavier fabrics made with yarns of the lower yarn number are less feltable. Thus, increasing the density of the fabric by using a heavier yarn or by knitting with more loops per inch tends to produce a more shrink-resistant fabric.

This result suggested that these two factors could be considered together. With woven fabrics, the parameter known as the "cover factor," F, is frequently used to define the fabric density; it is given by the relationship

$$F = \frac{T}{\sqrt{Y}},$$

where T is the number of picks or ends per inch and Y is the effective yarn number (the yarn number for singles; one-half the singles yarn number for 2-ply yarns, etc.). Peirce [6] analyzed the geometry of knitted fabrics and defined the density, ρ_k, in terms of the unit weight of the yarn, g, and the course and wale spacings, p and w, respectively. Combining several of his equations, the density is

TABLE VI. EFFECT OF BRADFORD VS. FRENCH SPINNING ON SHRINKAGE IN LAUNDERING OF UNTREATED WOOL

Fabric	Yarn No.	Fabric texture (wales/in.)	Fabric texture (courses/in.)	Type of spinning	Shrinkage in 5 Army mobile launderings Wales (%)	Shrinkage in 5 Army mobile launderings Courses (%)
Flat-knit tubing	26/1	27	35	Bradford	18	13
	26/1	27	33	French	18	8
Flat-knit socks	26/2	17	20	Bradford	27	19
	26/2	16	20	French	28	16
Flat-knit tubing	26/2	11	13	Bradford	46	38
	26/2	11	13	French	50	36
Rib-knit tubing	26/2	12	20	Bradford	29	16
	26/2	13	19	French	30	17

given to a first approximation by:

$$\rho_k = \text{constant}\ \frac{g}{(p+w)^2}.$$

Since Peirce's weight per unit length, g, is inversely proportional to the yarn number, Y, and the course and wale spacings vary as the reciprocal of the number of courses and wales per inch, the cover factor can be seen to be related to the density of knitted fabrics, as given by Peirce. The somewhat arbitrary procedure was therefore followed of calculating a "cover factor" for the present knitted fabrics, using the relationship

$$F = \frac{T}{\sqrt{Y}},$$

and taking as T the sum of the number of courses and wales per inch. The factor so calculated is clearly related to the density of packing of wool in a given area of knitted goods, and it has the virtue of extreme simplicity.

TABLE VII. SHRINKAGE OF UNTREATED KNITTED FABRICS OF APPROXIMATELY EQUAL TEXTURE AS A FUNCTION OF YARN NUMBER

Fabric	Yarn No.	Fabric texture (wales/in.)	Fabric texture (courses/in.)	Shrinkage in 5 Army mobile launderings Wales (%)	Shrinkage in 5 Army mobile launderings Courses (%)
Flat-knit tubing	15/2	13	17	25	12
	26/2	16	19	30	18
Rib-knit tubing	15/2	12	18	14	0
	26/2	12	20	29	16
	15/1	15	17	30	19
Flat-knit tubing	26/2	18	22	25	14
	15/1	19	22	24	15
	36/2	18	23	29	19
Flat-knit tubing	15/2	8	10	30	25
	26/2	11	13	46	38
Flat-knit tubing	36/2	20	26	22	13
	26/1	25	33	23	16
	26/1	25	28	24	13
	36/1	25	30	33	24

The "cover factors" so calculated were plotted against the felting shrinkages, the curves being shown by the circles in Figures 1 and 2 for the untreated flat- and 1 × 1 rib-knit fabrics, respectively. The correlation is quite good. One can estimate the felting for a wide variety of constructions and yarn types from the "cover-factor" values.

As a matter of general interest, an attempt was made to determine whether this relationship would also hold for other data. Accordingly, the data of Dutton [3] and of Cox *et al.* [2] were calculated in this way and plotted on the same curves. The plots (solid squares and open squares, respectively) are observed to fit very well to the present data, despite the considerable difference in the felting test methods used. This suggests that the observed relationship is of general usefulness, although the very good agreement between the present data and those of Dutton and Cox must be regarded as partly fortuitous, which is probably due to the fact that all the shrinkage tests involved were quite severe.

Effect of Level of Treatment

Comparison of the general shrinkage values in Tables I and II and in Tables III and IV reveal, as one would expect, that treatment for shrink-

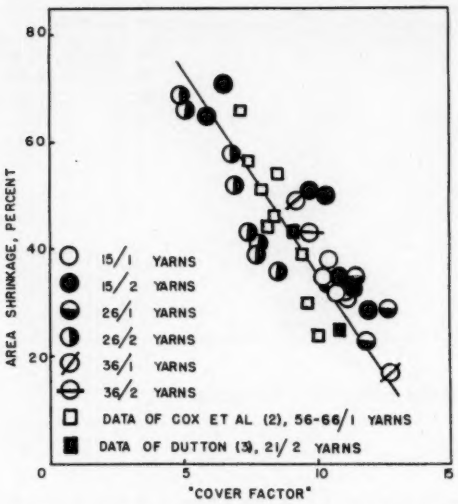

FIG. 1. *Shrinkage of untreated flat-knit fabrics in laundering as a function of cover factor.*

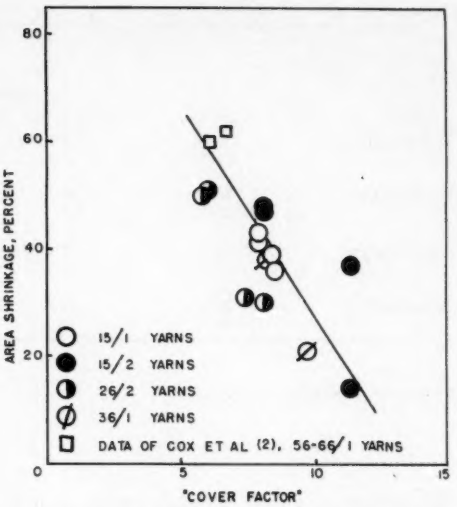

FIG. 2. *Shrinkage of untreated rib-knit fabrics in laundering as a function of cover factor.*

resistance is the largest factor in lowering feltability. An over-all view of this is given in Tables VIII and IX, which, in addition, give a picture of the magnitudes of the felting changes with continued laundering; these results are for the mild washing procedure, using low-titer soap as detergent.

The data demonstrate the importance of wool treatment in achieving acceptable shrink-resistance. In line with the discussion on pp. 103–4, there are socks (especially of the slack constructions) which are unsatisfactory as shrink-resistant garments because of inadequate construction, despite the overall reduction in felting when chlorinated wool is employed. This point is of great importance and hence merits repetition: specification of shrink-resistance is of itself insufficient, and further description with respect to the construction in which the wool is to be used is required. One may thus "tailor" a treatment (within limits) to a given construction, or, alternatively, one must provide a sufficiently tight construction for a given treatment in order to meet end-use requirements.

Summary and Conclusions

1. Knitting stiffness, and, to a much smaller extent, yarn twist, contribute to the felting behavior of knitted fabrics. Increase in the number of wales and courses per inch and in the twist can be used to effect appreciable improvement in laundering stability.

2. As the weight of the yarn used in a knitted structure is increased, the feltability decreases.

3. The "cover factor," which is a measure of the amount of wool packed into a unit area of fabric, and which is proportional to the wales and courses and inversely proportional to the square root of the yarn number, correlates well with the relative shrink-resistance of a construction.

4. Plying of yarns and type of spinning (Bradford *vs.* French) do not appear to affect feltability, other things being equal.

5. Application of a shrink-resistant treatment to the wool produces a greater effect in reducing laundering shrinkage than any modification of construction here employed. Construction variables must necessarily be considered in relation to the level of treatment nonetheless, since unsatisfactory stability may be found with shrink-resistant wools if the fabric construction is sleazy.

It is to be noted that the range of constructions considered in this experiment did not deviate too far from those considered normal in terms of conventional commercial practice. It is quite possible

TABLE VIII. SHRINKAGE IN MILD LAUNDERING OF FLAT-KNIT SOCKS

	Length shrinkage in laundering†						
	Untreated			Mild treatment		Optimum treatment	Severe treatment
Yarn Code No.*	5 cycles (%)	10 cycles (%)	20 cycles (%)	10 cycles (%)	20 cycles (%)	20 cycles (%)	20 cycles (%)
1—Slack knit	8	18	25	10	14	3	—
1—Tight knit	7	15	22	10	8	3	—
2—Slack knit	11	16	26	5	8	—	2
2—Tight knit	8	17	24	1	4	5	—
3—Slack knit	12	16	24	10	14	4	1
3—Tight knit	10	13	22	7	10	2	1
4—Slack knit	7	15	23	8	13	4	1
4—Tight knit	6	12	18	6	6	2	1
5—Slack knit	9	19	26	6	9	—	—
5—Tight knit	6	14	19	6	5	—	—
6—Slack knit	7	13	22	—	—	2	2
6—Tight knit	6	7	16	—	—	2	2
7—Slack knit	11	23	28	12	14	6	5
7—Tight knit	10	19	25	10	12	6	2
8—Slack knit	13	18	30	—	—	3	5
8—Tight knit	9	13	25	—	—	1	2
10—Slack knit	9	19	28	—	—	2	1
10—Tight knit	5	13	22	—	—	2	2

* The numbers correspond to the listing presented in the Materials section (page 103).
† Measured with the Schiefer device (Supplement to Fed. Spec. CCC-T-191a).

TABLE IX. SHRINKAGE IN MILD LAUNDERING OF 1 × 1 RIB-KNIT SOCKS OR TUBING

	Length shrinkage in laundering†						
	Untreated			Mild treatment		Optimum treatment	Severe treatment
Yarn Code No.*	5 cycles (%)	10 cycles (%)	20 cycles (%)	10 cycles (%)	20 cycles (%)	20 cycles (%)	20 cycles (%)
1 —Slack knit	11	26	33	17	19	9	5
1 —Tight knit	11	16	20	4	6	0	3
2 —Slack knit	14	23	32	9	13	5	5
2 —Tight knit	7	9	21	4	9	2	—
9‡—Slack knit	8	12	18	—	—	—	—
9‡—Tight knit	6	6	8	—	—	—	—

* The numbers correspond to the listing presented in the Materials section (page 103).
† Measured with the Schiefer device (Supplement to Fed. Spec. CCC-T-191a).
‡ Tubing specimens.

that combinations of variables which would give considerably better felting control than was found here, and which are not now used in industry, exist.

Acknowledgment

Grateful acknowledgment is made to Messrs. John Gardiner and Fritz F. Kobayashi of the Ames Worsted Company, who arranged for treatment of the wool top.

Many of the measurements were performed by Mrs. Virginia G. Moran (Harris Research Laboratories) and Miss Gertrude Ardis (Quartermaster Research and Development Laboratories).

Literature Cited

1. Bogaty, H., Sookne, A. M., and Harris, M., TEXTILE RESEARCH JOURNAL **20**, 270 (1950).
2. Cox, A. B., Hindson, W. R., Wilding, J. A., and Young, F. S., "Shrinkage Testing of Wool Fabrics with Special Reference to Underwear," Defense Research Laboratories, Commonwealth of Australia, Dec. 1949.
3. Dutton, W. A., *J. Text. Inst.* **37**, P212 (1946).
4. Dutton, W. A., *J. Text. Inst.* **40**, P638 (1949).
5. Frishman, D., and Harris, M., U. S. Patent 2,466,695 (Apr. 12, 1949) (assigned to Harris Research Laboratories).
6. Peirce, F. T., TEXTILE RESEARCH JOURNAL **17**, 123 (1947).

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The Technical Possibilities for a Regenerated Silk*

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Contribution from the Textile Research Institute and the Departments of Chemistry and Chemical Engineering, Princeton University, Princeton, N. J.

Abstract

The molecular properties of silk fibroin are such as to make the regeneration of silk worthy of serious consideration. Not only is the molecular weight such as to indicate at least 500 units in the polymer, but, also, the component residues are among the simplest amino acids, without bulky side groups. Thus, the interchain attraction is the highest of several representative polymers. The mechanical problems of silk regeneration are not easily overcome, however. Many solvents degrade the fibroin appreciably, and, so far as is known, aqueous solutions of concentration comparable to that found in the silkworm have not been made. The structural simplicity which gives rise to good polymer properties is also conducive to instability of aqueous solutions. While important in an over-all appraisal of silk regeneration, the economic problems are not discussed in this paper.

IN 1947 Coleman and Howitt reported the results of their study on the properties and constitution of silk fibroin in an article [1] which reawakened the interest of chemists in the structure of one of the simplest naturally-occurring protein molecules known. This structural simplicity, a term used in a relative sense with respect to other naturally-occurring proteins, is now believed to be largely responsible for the unique properties of silk fibroin solution—properties which have greatly complicated the many efforts to investigate the fibroin molecule by conventional laboratory methods.

The work of Coleman and Howitt stimulated Taylor and Jolley to investigate silk solutions, and their interest in this problem has been communicated to the Textile Research Institute [13], where the inter-relationship of fiber structure to mechanical behavior constitutes one of the major objectives of research. The study of regenerated silk fiber manufacture was a logical extension of that interest.

In order to compete successfully with other fibers, regenerated silk must have the strength of rayon (that is, be stronger than any other protein fiber, with the exception of natural silk); should be in the form of a uniform continuous filament, which would overcome many of the expensive processing difficulties encountered with natural silk; and, most important of all, should possess those "silky" qualities the public has always associated with the natural product. This last requirement is essential if the fiber is to be called regenerated silk. Although a satisfactory solution of the technical problems involved in the manufacture of regenerated silk must take into account such economic factors as the price of raw materials, the cost of manufacture, and the potential market, it would be futile to try

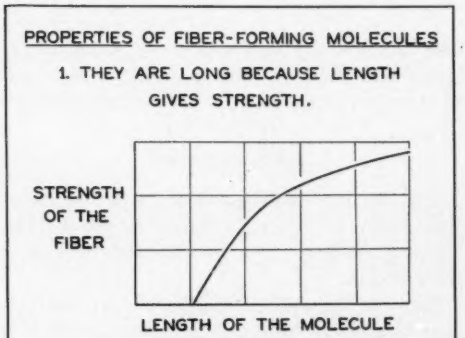
PROPERTIES OF FIBER-FORMING MOLECULES
1. THEY ARE LONG BECAUSE LENGTH GIVES STRENGTH.
STRENGTH OF THE FIBER
LENGTH OF THE MOLECULE

FIG. 1.

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to estimate these items without a definite process in mind. The present paper, therefore, is limited to the technical aspect of regeneration.

Molecular Structure of Fiber-Forming Substances

Before the structure of silk is considered, it would be well to review those molecular properties which are recognized as essential features of all of the better fiber-forming substances. Firstly, the molecules must be sufficiently long to permit their inherent attractive forces to bind them together so that the application of tension to the resulting fiber does not readily pull them apart. The qualitative relationship of molecular length to strength is illustrated in Figure 1. The molecules must also possess properly spaced centers of attraction which will give rise to strong forces of cohesion between adjacent molecules, as shown in Figure 2. A third factor of importance is that the molecules should be without bulky neutral side groups which prevent the main parts of the molecular chains from approaching each other closely and thus limit the action of intermolecular cohesive forces (see Figure 3). Finally, the molecular aggregates in fiber form must have high melting points and low solubility in common solvents.

Molecular Properties of Silk

Polymer Length

It might be inferred from knowledge of the properties of silk fibers that the constituent molecules would fill the above requirements very well. Experimental observations on fibroin structure bear out this conclusion. Coleman and Howitt reported a molecular weight of 33,000 for silk fibroin, based on osmotic pressure measurements, and there are indications [11] that the correct value may be much higher. In any case, silk fibroin has more than ample molecular length to make a good fiber. Its chain length may be calculated from amino acid equivalent weights to be in the vicinity of 400–500 polymer units (or 1750 Å.), based on the Coleman and Howitt molecular weight. The values in Table I show how well silk fibroin compares in this respect with other fibers, such as nylon and rayon.

TABLE I. LENGTH OF FIBER MOLECULES

Substance	Approximate number of units in polymer	Approximate length of molecule (Å.)
Silk fibroin	500	1750
Nylon [12]	220	1900
Rayon	500	2600
Cotton	3000	15000

Amino Acid Composition [5]

It can be seen from Table II that silk fibroin predominates in those amino acids which contain few side groups, whereas other proteins contain relatively large amounts of the bulky polyamino and polycarboxylic amino acids.

The fact that approximately 75% of the silk molecule is composed of the three simplest amino acids—glycine, alanine, and serine—is most impor-

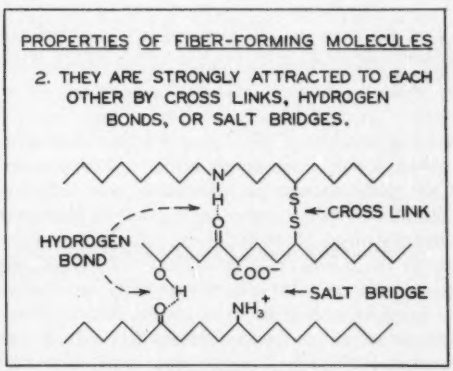
PROPERTIES OF FIBER-FORMING MOLECULES
2. THEY ARE STRONGLY ATTRACTED TO EACH OTHER BY CROSS LINKS, HYDROGEN BONDS, OR SALT BRIDGES.
CROSS LINK
HYDROGEN BOND
SALT BRIDGE

FIG. 2.

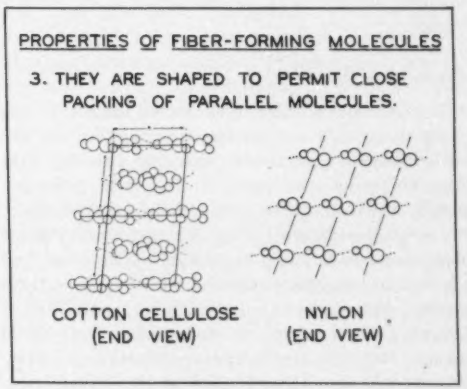
PROPERTIES OF FIBER-FORMING MOLECULES
3. THEY ARE SHAPED TO PERMIT CLOSE PACKING OF PARALLEL MOLECULES.
COTTON CELLULOSE (END VIEW)
NYLON (END VIEW)

FIG. 3.

TABLE II. AMINO ACID CONTENTS OF FIBER PROTEINS

Amino acid	Grams of amino acid per 100 g. of: Silk	Casein	Wool
Glycine	42.30	1.90	6.50
Alanine	24.50	3.50	4.40
Serine	16.24	5.87	9.41
Tyrosine	10.60	6.28	5.80
Proline	1.50	10.54	6.75
Histidine	0.47	3.24	0.70
All others observed	16.11	79.02	76.90

tant in considering the attractive forces which adjacent fibroin molecules will have for each other. Each amino acid residue will furnish at least one amino group and one carbonyl group, which behave as the centers of attraction between the long molecules, as shown in Figure 4. They supply the elements for hydrogen-bond formation at frequent intervals along the molecular chain. In a chain made up of glycine, alanine, and serine, the average interval between hydrogen-bond centers is 1.7 Å.; in nylon the spacing is of the order of 4.3 Å.

Molar Cohesion

Mark [8] has expressed these interchain attractions of linear high polymers in terms of a molar cohesion, a property which takes into account the spacing of the attractive centers, the packing characteristics of the chains, and the energies with which the chains are drawn together. Silk fibroin ranks the highest of all polymers on a scale of molar cohesion with a value of 9.8 kg.-cal./mole, as compared to 6.2 for cellulose, 5.8 for nylon, 4.8 for cellulose acetate, and 1.3 kg.-cal./mole for natural rubber.

Amino Acid Distribution

Coleman and Howitt [1] subjected the silk fibroin molecule to mild tryptic digestion, which preferentially destroys the tyrosine elements, leaving fairly long fragments estimated to have a molecular weight of about 10,000 (one-third of the length of the original molecule). Drucker and Smith carried this procedure one step further [2]. They analyzed the residual fragments (estimated by them to have a molecular weight of only 8,000) by the method of hydrolysis and paper chromatography and found present *only* the three amino acids previously mentioned—glycine, alanine, and serine. They concluded that approximately two-thirds of the fibroin

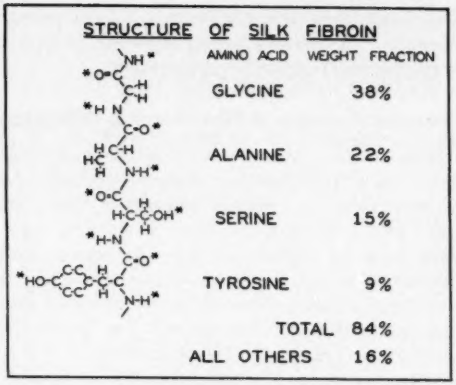

FIG. 4. *Amino acid distribution in silk fibroin. The starred atoms are those effective in interchain hydrogen bonding.*

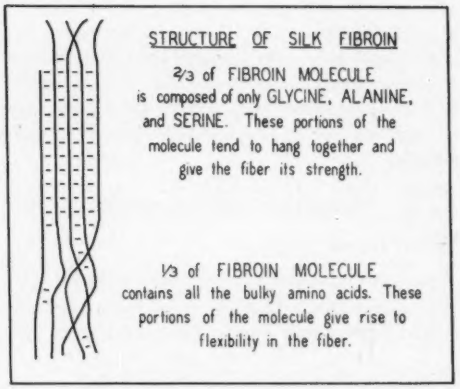
STRUCTURE OF SILK FIBROIN
2/3 of FIBROIN MOLECULE is composed of only GLYCINE, ALANINE, and SERINE. These portions of the molecule tend to hang together and give the fiber its strength.
1/3 of FIBROIN MOLECULE contains all the bulky amino acids. These portions of the molecule give rise to flexibility in the fiber.

FIG. 5. *Diagrammatic representation of silk fibroin molecules in the ordered and disordered regions of the silk fiber.*

molecule consists of thin linear portions containing residues of only these simple acids. These portions of the molecule will pack regularly with adjacent molecules to form ordered or crystalline regions in which the forces of attraction are strong, thus giving rise to the strength of the fiber. The remaining third of the molecule is in shorter sections in which the residues with bulky side groups occur. These sections are primarily amorphous and give rise to the flexibility and elasticity associated with silk. (See Figure 5.)

The effect of these bulky side groups in preventing close cohesion between molecular chains is especially well demonstrated in Figure 6, which is a photograph of scalar molecular models of silk fibroin and casein. The black spheres represent carbon atoms; those marked O, oxygen atoms; and the other gray spheres, hydrogen atoms. The oxygen atoms are in carbonyl groups or hydroxyl groups which give rise to hydrogen bonds. In the case of silk these groups are found near the surface of the molecule, but in casein the bulky hydrocarbon side groups tend to submerge the carbonyl groups and to prevent them from forming close hydrogen bonds with neighboring molecules. Thus, as strong a fiber cannot be obtained from casein as from silk.

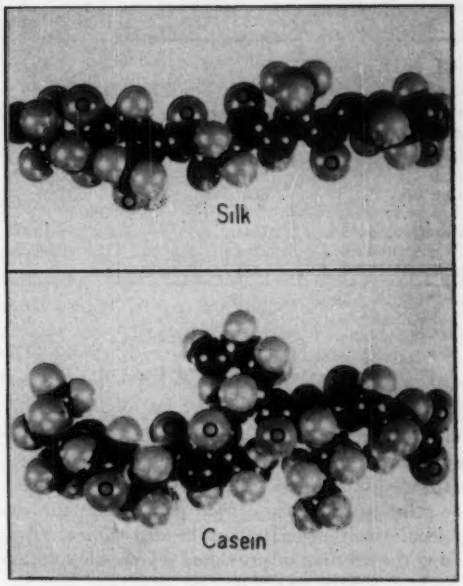

FIG. 6. *Photograph of molecular models of silk and casein proteins. The atoms marked with an O represent oxygen atoms, which are effective in interchain hydrogen bonding.*

Problems of Silk Regeneration

From the foregoing it may be concluded that, at least from a structural point of view, it should be possible to make a good textile fiber from silk fibroin. Attention must now be turned to the methods and problems involved in the regeneration process.

In a wet spinning process such as might be used to regenerate silk, fiber material is first dissolved in a suitable solvent in order to prepare a spinning dope. This viscous dope is then forced through a spinneret or disc with fine holes into a precipitating bath. The resulting filaments are hardened, washed, stretched, and dried preparatory to final twisting and processing.

Four types of solvents have been proposed for silk regeneration [6]. One consists of concentrated phosphoric or sulfuric acids, which will dissolve either the fibroin or whole raw silk fiber. Concentrated salt solutions, such as sodium thiocyanate solution, have also been suggested. Silk is soluble in alkaline copper solution, such as cupriethylene diamine and cuprammonium hydroxide. Finally, several methods of preparing water solutions have been considered since the original silk solution prepared by the silkworm is regarded as a water solution.

Aqueous Solutions for Silk Regeneration

Because of the degradation known to occur in acid or alkaline solutions, attention has been directed to the use of approximately neutral aqueous solutions as the most suitable for silk regeneration. A number of patents [3, 4] have been issued on methods for making a concentrated water solution of silk by first dissolving the silk in liquid ammonia and then adding water as the ammonia is boiled off. Coleman and Howitt [1] prepared a water solution by dissolving silk in cupriethylene diamine and then removing this reagent by dialysis. They were able to concentrate the aqueous solution to 10% silk by means of vacuum drying. Fibers drawn from this solution had about one-half the strength of natural silk but were poorly oriented. Jolley and Taylor [7] extended this method by concentrating the dialyzed silk solution by freeze-drying. In this way they obtained a solid silk fibroin which would dissolve in a neutral buffer solution to a maximum concentration of 10%–12% by weight.

The results of investigations by Jolley and Taylor on the nature of silk in water solution have led to speculation on the changes in shape and aggregation which take place. In cupriethylene diamine solution, the individual silk molecules are surrounded by cupriethylene groups which protect them from the attractive forces of other silk mole-

TABLE III. MECHANICAL PROPERTIES OF SILK FIBERS

Material	Condition†	Modulus (g./sq.cm.)	Denier	Breaking load (g.)	Breaking load (g./den.)	Extension at break (%)	Yield point (g.)	Yield point Extension (%)
[c]Raw silk	Dry	9.5×10^7	3.32	11.3	3.38	17.9	2.4	0.98
[c]Degummed silk	Dry	13.0×10^7	1.18	4.21	3.65	9.5	1.0	0.87
[s]Raw silk	Dry	14.6×10^7	20.2	77.5	3.85	21.8	23.4	1.00
[s]Raw silk	Wet	*	20.2	59.1	2.93	29.2	*	*
[s]Regenerated silk *A*	Dry	9.7×10^7	72.4	114.2	1.58	26.0	53	0.96
[s]Regenerated silk *A*	Wet	*	72.4	58.7	0.81	21.6	*	*
[s]Regenerated silk *B*	Dry	6.2×10^7	84.9	73.5	0.87	11.8	50	1.20
[s]Regenerated silk *B*	Wet	*	84.9	39.7	0.47	11.8	*	*

[c] Cocoon fiber (2 filaments).
[c] Cocoon filament.
[s] Skein form.
* No well-defined Hookean region.
† "Dry" means conditioned at 70° F and 65% R. H. "Wet" means soaked in water and sprayed with water during test.

cules. By neutralizing or by dialysis this protective layer is stripped from the molecules, leaving them suspended in solution. In time, without agitation, the solution will form a rigid gel because the silk molecules will associate to a limited extent. Agitating the solution or providing a large air-solution interface greatly speeds up this process of aggregation. If the clusters of silk particles so formed become large enough, the solution becomes cloudy and the silk precipitates. The organization of the silk molecules in these precipitated particles may be quite unlike that of the silk spun by the silk worm because of the differences in agitation and air-solution interface. This tendency for the silk fiber to "denature" or coagulate in the form of a precipitate is unquestionably due to the same strong intermolecular attractive forces which cause the substance to form well-ordered and strong fibers. Jolley and Taylor found no significant difference between the composition of the silk in solution and that which precipitated, so that the type of aggregation is the only conceivable variation remaining.

While the preparation of neutral buffered water solutions of silk fibroin may be of interest from a theoretical point of view, experience indicates that the preparation of a dope for fiber spinning by this method may be highly impractical. In the first place, the water solutions are low in concentration and difficult to handle, the silk readily precipitating on standing or with slight agitation. A second important reason for rejecting dilute water solutions for regenerating purposes is their low viscosity. Good wet spinning through multiple spinnerets requires dopes with viscosities 100–5,000 times that of water. The worm is not faced with this viscosity requirement since it has the equivalent of a separate

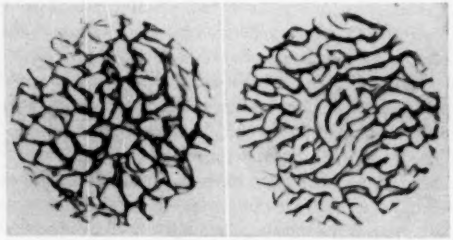

FIG. 7. *Photomicrographs of the cross sections of degummed silk fibers* (left) *and regenerated silk fibers* (right). *Approximate magnification, 200×.*

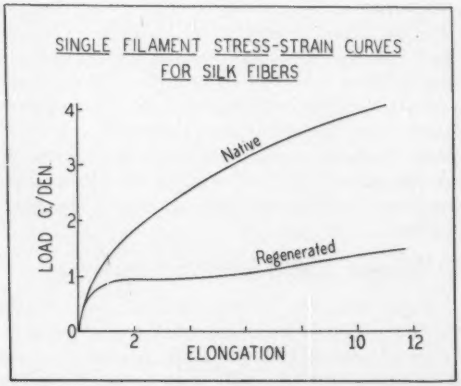

FIG. 8.

TABLE IV. PROPERTIES OF REGENERATED PROTEIN FIBERS

	Moisture regain (%)	Tenacity (g./den.)		Elongation to break (%)	
		Dry	Wet	Dry	Wet
Regenerated silk *A*	8	1.6	0.8	26	22
Regenerated silk *B*	9	0.9	0.5	12	12
Aralac	13	0.8	0.4	30	100
Casein (U.S.D.A.)	13	1.2	0.6	50	45
Vicara	13	0.8	0.4	42	50
Wool	17	1.4	1.2	35	45
Silk (degummed)	10	4.0	3.4	16	26

feed pump and reservoir tank for each single filament spinneret. Such a system would not be practical in industrial production.

Experimental Results

Two samples of regenerated silk fiber were obtained through the courtesy of Mr. H. Lee Moss of the International Silk Association (U.S.A.), Inc. Nothing is known of the history of sample *A*, but sample *B* was spun from a cuprammonium hydroxide solution. Tests were made at controlled room conditions (70°F and 65% R.H.) and with the sample soaking wet. The averages of 25 tests are reported in Table III and compared with data on other protein fibers in Table IV [9, 10]. The theoretical expectations in favor of a good regenerated silk fiber are confirmed if the results are compared with those for other protein fibers, but compared with those for native silk the results are far from satisfactory. Photomicrographs of the two forms of silk are shown in Figure 7.

Summary

Regenerated silk, at the moment, is far from meeting the requirements laid down earlier in this paper. One indication of the improvement which would have to be made in obtaining a mechanically acceptable regenerated silk is shown by a comparison of stress-strain curves for native (degummed) and regenerated silk fibers in Figure 8. Above all, the regenerated silk samples inspected did not have the silky hand and appearance that one associates with the natural product. The Department of Agriculture Eastern Regional Research Laboratory, on the other hand, has made casein fiber with the soft touch and luster of silk, and the warmth and strength of wool. The goal of making an acceptable casein fiber does not seem to be impossible of attainment and there is reason for confidence that the same could be accomplished for silk.

Silk appears to have a molecular structure which should make it superior to all other proteins for making a regenerated fiber, but the same structural features complicate the regeneration process. It seems possible that the problems involved could be solved and an acceptable fiber produced if the economics of matter justified it.

Literature Cited

1. Coleman, D., and Howitt, F. O., *Proc. Roy. Soc. (London)* **A190**, 145 (1947).
2. Drucker, B., and Smith, S. G., *Nature* **165**, 196 (1950).
3. Fink, H., and Rossner, R., U. S. Patents 1,989,005 (Jan. 22, 1935) and 2,012,382 (Aug. 27, 1935).
4. Fink, H., *et al.*, U. S. Patent 2,010,918 (Aug. 13, 1935).
5. Hoover, S. R., Kokes, E. L., and Peterson, R. F., TEXTILE RESEARCH JOURNAL **18**, 427 (1948).
6. Howitt, F. O., "Bibliography of the Technical Literature on Silk," London, Hutchinson's Scientific and Technical Publications, 1946, pp. 70 *et seq.*
7. Jolley, H. R., and Taylor, H. S., Unpublished results.
8. Mark, H., *Ind. Eng. Chem.* **34**, 1341 (1942).
9. Schmidt, A. X., and Marlies, C. A., "Principles of High Polymer Theory and Practice," New York, McGraw-Hill, 1948, Appendix B.
10. Peterson, R. F., McDowell, R. L., and Hoover, S. R., TEXTILE RESEARCH JOURNAL **18**, 744 (1948).
11. Smith, H. G., Private communication, 1950.
12. Taylor, G. B., *J. Am. Chem. Soc.* **69**, 638 (1947).
13. Taylor, H. S., Address before the Annual Meeting of the Textile Research Institute, Dec. 1, 1949.

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Correlation Studies of Accelerated and Natural Weathering Tests of Protectively Finished Cotton Duck

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Abstract

Artificial and natural weather exposure tests were made with unfinished and with protectively finished cotton duck samples. The treating agents employed were chiefly mineral pigments, film-forming resins, and vat dyes, alone and in combinations.

The finishes were ranked in order of excellence on the basis of amounts of original strength retained by individual samples in both types of exposure.

The results of the natural and accelerated tests were compared and then correlated by a statistical method and by a simple computation of agreement among groups of good, intermediate, and poor performance. Although statistical interpretation of the data indicated a positive correlation between the 2 types of tests, the relationship was not sufficiently constant to justify reliance on the accelerated techniques employed in predicting the behavior of finished cotton textiles in outdoor service conditions.

THERE IS a need for a dependable accelerated method of testing the serviceability of textile products designed for outdoor use. In screening a group of experimental weather-resistant finishes, for example, it would be of obvious advantage to have available a rapid method for testing that would dispense with time-consuming outdoor exposures, which usually require from 6 months to a year.

Because of a general lack of information in this field, as well as advantages to be gained in work on protectively finished cotton fabrics, the authors decided to investigate the possibilities of accelerated weathering. It is clear that in order to be of value the results of such artificial testing methods must have some degree of practical correlation with those of natural weathering. It was recognized, however, that a universal or standard weathering pattern does not exist. Weather is a complex of several unstable degradative factors, and its effects on cotton textiles, varying from time to time and from place to place, are never precisely reproducible.

Strength-loss data were available from a considerable range of experimental protective finishes applied to cotton duck and exposed for a year to natural weather [1]. By submitting replicate samples to accelerated weathering methods, it was possible to determine the correlation that might exist between the two types of tests. The exposure conditions employed in accelerated weathering for these tests were aimed at producing results resembling those caused by the action of sun and rain in outdoor weather. Comparisons could then be made with the degradative influence of New Orleans weather, which is believed to be sufficiently representative to indicate satisfactorily the effectiveness of the different finishes examined. The results and conclusions on the degree of correlation possible with the accelerated weathering techniques employed are set forth in this paper.

General Considerations

Accelerated weathering devices such as those employed in the paint industry attempt to simulate weather exposure by continuously irradiating specimens with light that is rich in ultraviolet while subjecting them to alternate cycles of wetting and

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TABLE I. EXPERIMENTAL FINISHES ON BLEACHED DUCK (SERIES *A*)

Sample designation	Finish
A	Unfinished control
B	Methyl methacrylate resin
C	Oil-modified alkyd resin
D	Urea formaldehyde resin
E	Lead chromate (*in situ*)
F	Mineral dye
G	Lead chromate (*in situ*) plus alkyd resin
H	Lead chromate (*in situ*) plus urea formaldehyde resin
I	Mineral dye plus urea formaldehyde resin
J	Lead chromate dispersed in urea formaldehyde resin
K	Lead chromate dispersed in alkyd resin
L	Milban dispersed in alkyd resin
M	Sienna dispersed in urea formaldehyde resin
N	Chromic oxide dispersed in urea formaldehyde resin
O	Antimony oxide dispersed in urea formaldehyde resin
P	Monastral Blue dispersed in urea formaldehyde resin
Q	Milban dispersed in urea formaldehyde resin
R	Basic copper carbonate dispersed in urea formaldehyde resin

TABLE II. EXPERIMENTAL FINISHES ON BLEACHED DUCK (SERIES *B*)

Sample designation	Finish
a	Undyed, unfinished control
b	Green dyed only
c	Blue dyed only
d	Yellow dyed only
e	Brown dyed only
f	Undyed, urea formaldehyde finish
g	Undyed, melamine formaldehyde finish
h	Undyed, precondensed urea formaldehyde finish
i	Green dyed, urea formaldehyde finish
j	Blue dyed, urea formaldehyde finish
k	Yellow dyed, urea formaldehyde finish
l	Brown dyed, urea formaldehyde finish
m	Green dyed, melamine formaldehyde finish
n	Blue dyed, melamine formaldehyde finish
o	Yellow dyed, melamine formaldehyde finish
p	Brown dyed, melamine formaldehyde finish
q	Green dyed, precondensed urea formaldehyde finish
r	Blue dyed, precondensed urea formaldehyde finish
s	Yellow dyed, precondensed urea formaldehyde finish
t	Brown dyed, precondensed urea formaldehyde finish
u	Undyed, zinc chromate (*in situ*), urea formaldehyde finish
v	Undyed, zinc chromate (*in situ*), melamine formaldehyde finish

drying. Young [8] states that numerous reports on the subject indicate the common difficulty of obtaining satisfactory agreement between natural and accelerated weather tests.

The somewhat limited references in the literature indicate that attempts to apply accelerated weathering to textiles have had no greater success. The use of carbon arc light in determining the resistance of dyes to fading has become well established, but comparatively little attention has been given to the degradative effects suffered by yarns or fabrics during such exposure. An exception to this is the recent work on fabric deterioration during controlled fading tests reported from Pennsylvania State College by Lyle and coworkers [5, 6], who used a modified form of an apparatus that was originally constructed by Appel and Jessup [2] to study the accelerated aging of silk. This equipment was also employed by Chapman [3] to investigate the changes that it caused in textiles other than silk.

Clibbens and Ridge [4] have demonstrated that for cotton yarn progressively tendered by acid hydrolysis a practically linear relationship exists between the increasing breaking-strength losses and the corresponding increases in the cuprammonium fluidity of the chemically modified cotton. Tests at the Southern Regional Research Laboratory have shown that natural weathering of bleached cotton duck produces strength-fluidity relationships which approached those produced by acid hydrolysis. For artificial weathering, however, the fluidity values were inordinately low when compared with those of the naturally weathered replicates at points of equal strength losses.

Since it appeared inadvisable to employ fluidity values for measuring the amounts of chemical degradation caused in replicate samples by the two kinds of tests, reliance was placed entirely on the comparative strength losses suffered by the samples.

Fabric and Finishes

The comparative tests were made with two groups of fabric samples—designated series *A* and *B*—each series comprising several experimental weather-resistant finishes. The fabric was a standard 8-oz. Army duck, counting 52 warp by 40 filling t.p.i. and weighing approximately 10.1 oz. per sq. yd. It had been scoured and lightly bleached before finishing.

The 17 protective treatments applied in series *A* were principally clear, film-forming resins and mineral pigments, used either separately or in combinations (Table I). Two pigment treatments—lead chromate and mineral khaki—were precipitated directly in the fabric by a two-bath (double decomposition) method, and a part of each of these samples was given a resin finish before exposure. The other pigments in this group were dispersed in resin monomer solutions or emulsions, and the cloth samples impregnated with these combinations on a laboratory padder. They were then dried and heat-treated as required for resin polymerization.

The 21 samples of series *B* were prepared chiefly to investigate the effect of vat dyes as protectants when used either alone or in combination with resin finishes (Table II). The dyes chosen—blue, green, brown, and yellow—were typical Indanthrene types of good fastness, and were applied by the pad-jig method to give approximately 8.0% dyeings. Additions in series *B* to the alkyd and urea formaldehyde resin finishes used in series *A* were melamine formaldehyde and a precondensed urea formaldehyde resin. An additional *in situ* pigment, zinc chromate, was included in this group.

All formulations in both series were calculated to give approximately 2.0% pigment and 5.0% resin (on the dry weights of the goods).

Exposure Methods

Natural weather exposure tests of treated and control samples were made in the manner described in a previous publication [1]. Briefly, 1-yd. samples were supported at an angle of 45° from the vertical on wooden racks which faced south, and were so placed that there was unobstructed sunlight exposure. The samples were left out to weather for 12 mo., a period sufficient to insure good differentiation between the treatments. Series *A* and series *B* were exposed in consecutive years.

Simultaneously with the natural weather exposure tests, accelerated weathering tests were carried out on replicate samples from the two series. The accelerated weathering tests were made in an accelerated weathering unit in which the samples were mounted on a vertical revolving cylindrical rack and rotated at a speed of 1 revolution every 2 min. about a "Sunshine" carbon arc lamp supplied with 60 amp. at 50 v. A.C. The mean distance of the samples from the light source was 19 in. The revolving sample rack and the arc were totally enclosed in a covered cylindrical sheet-metal tub which was ventilated by a fan exhausting from the top of the arc housing. A solenoid-operated distilled-water spray could be set to wet the samples on any predetermined schedule. A ring of jets was installed in the bottom of the tub to sweep filtered air across the samples. This ventilation, together with evaporation from a heavy cotton bagging hung around the outside of the rotating sample rack and kept saturated with water, maintained lower sample temperature and higher ambient air humidity than that normally obtained in the unmodified machine. Slip rings installed on the hub of the revolving rack made possible the continuous recording of sample temperatures by means of a thermocouple.

The series *A* group of samples subjected to accelerated tests were exposed in replicates under 3 sets of conditions, varied in an attempt to obtain results that would approximate those of actual weathering: (1) following the recommended procedure of using distilled-water spray on the samples, accompanied by 500 hrs. of irradiation with Corex glass shields around the carbon arc light; (2) using the spray, with 50 hrs. of irradiation by the unshielded arc; (3) without spray, with 50 hrs. of irradiation by the unshielded arc.

The replicate samples of series *B* were exposed to accelerated testing only under condition (2).

When spray was used the samples were wetted for 5 min. in each hr., a cycle that allowed them to dry thoroughly between wettings. Irradiation was continuous except for changes of carbons, and sample surface temperatures were maintained, when dry, between 40°C and 50°C in ambient air of approximately 35% R.H.

The samples in any one test were exposed simultaneously.

Measurement of Exposure Effects

The effectiveness of the finishes was judged on the basis of the percentage of original breaking strength that was retained by individual samples after exposure. The breaking-strength tests were made on 10 strips of fabric cut 6 in. long in the warp direction and 1½ in. wide; the original but unexposed samples were frayed to a 1-in. width. After exposure, samples were frayed to a thread count equal to the number of warp yarns in 1 in.

of the unexposed material. A pendulum type of strength tester was used, with 3 in. between the jaws. The samples were broken after conditioning in an atmosphere of 65% R.H. and 70°F.

Test Results

In Table III are shown the percentages of original breaking strength retained by replicate samples of series *A* after the exposures. Table IV gives comparable strength data for the samples of series *B*.

It is apparent that the finishes comprising series *A* differ widely in individual effectiveness during exposure to natural weather. The data show that several of these finishes preserved the fabric almost completely through a natural degradative process that reduced by one-half the original breaking strength of the untreated control sample, while two of the treatments were either negative or actually harmful in effect. The average strength retained for the 18 samples in this test was 74%.

The series *B* samples tested the following year were subjected to somewhat more severe conditions than those for series *A*, as indicated by the greater strength loss of the series *B* control sample. The data on series *B* also showed considerable variation in the effectiveness of the different finishes. Only a moderate protective action could be attributed to the vat colors with which several of the samples were dyed, although as a group the dyed but unfinished samples were somewhat more resistant than the undyed control. The average strength retention for the 22 samples in this test was 56%.

In the accelerated tests with series *A* samples under condition (1), the duck was degraded so slowly that the untreated control retained 84% of its original strength, and the average strength retention for the 18 samples was 83%. The method appeared incapable of giving the desired acceleration effect, and was therefore not used again.

Exposure to the unscreened arc with spray, condition (2), and to the unscreened arc alone, condition (3), broke down the samples rapidly, and 50 hrs. in these tests produced strength losses in the controls that exceeded the corresponding loss after 12 mo. of natural weathering. The average strength retention for the 18 samples of series *A* was 59% for the condition (2) test; 71% for the condition (3) test.

TABLE III. EFFECT OF EXPOSURE TO NATURAL AND TO ACCELERATED WEATHERING ON BREAKING STRENGTH OF FINISHED DUCK SAMPLES (SERIES *A*)

Sample designation	Breaking strength retained: Natural weather (12 mo.) (%)	Accelerated weather (condition (1)) (%)	Accelerated weather (condition (2)) (%)	Accelerated weather (condition (3)) (%)
A	50	84	27	44
B	37	69	26	52
C	48	72	31	47
D	71	90	57	80
E	82	79	—*	59
F	57	68	80	76
G	81	85	76	60
H	99	89	77	87
I	66	73	88	94
J	96	100	71	79
K	87	83	54	63
L	57	70	37	53
M	98	84	65	83
N	97	91	57	78
O	78	92	67	80
P	76	85	71	70
Q	74	100	63	76
R	69	84	70	88
Average	74	83	59	71

* Sample E omitted in this test.

TABLE IV. EFFECT OF EXPOSURE TO NATURAL AND TO ACCELERATED WEATHERING ON BREAKING STRENGTH OF FINISHED DUCK SAMPLES (SERIES *B*)

Sample designation	Breaking strength retained: Natural weather (12 mo.) (%)	Accelerated weather (condition (2)) (%)
a	29	32
b	54	67
c	51	80
d	43	62
e	32	59
f	100	94
g	63	69
h	44	67
i	100	100
j	92	100
k	60	100
l	94	100
m	51	91
n	60	92
o	42	88
p	45	76
q	46	82
r	55	85
s	35	78
t	49	77
u	48	73
v	38	66
Average	56	79

Exposure of the series *B* samples to the unscreened arc plus spray, condition (2), the only accelerated test applied to this series, resulted in a strength retention of 32% for the control sample, which was close to the 29% retained by the replicate sample in the natural weather exposure. As a whole, however, the treated samples of series *B* proved to be more resistant in the accelerated than in the natural weather exposure, the average strength retentions for the 22 samples in the two tests being 79% and 56%, respectively.

Agreement in Test Results

The comparative performance of the series *A* samples, as shown by the individual strength-retention data (Table III), reveals a general lack of agreement between the natural and accelerated weathering tests that seriously affects the usefulness of such accelerated testing methods. The series *B* test results (Table IV) are somewhat less erratic, but here also are found instances of inconsistent performance. An examination of the correlation existing between these different test results can be made by several methods.

A graphic comparison is given in Figures 1, 2, and 3 for series *A* and in Figure 4 for series *B*. In these figures the samples were arranged in the order of their decreasing percent strength retentions shown in the natural weather exposure tests, and their individual values pointed off against a scale of 100. The points were then connected to form graphs that descend continuously, although somewhat irregularly, from left to right. Values determined for replicate samples in the accelerated tests were similarly indicated, and their points connected by broken lines.

If the specimens had ranked in the same order of excellence in the natural and artificial exposure tests, both lines would descend continuously toward the right; they would not have to be coincident, have the same slope, or be uniform in slope throughout. The figures show, however, many points of divergence among the accelerated test results from this general left-to-right pattern. The extent of agreement in the different tests can be examined statistically.

The data were compared by computing correlation coefficients using Spearman's "footrule" [7], a method which is satisfactory when only a rough approximation of the correlation based on ranks is desired. The specimens are listed in order of merit as ranked by one of the tests. In an adjacent column is placed the rating of each specimen as ranked by the other test. The measure of agreement between the two tests can be expressed by the coefficient R in the formula

$$R = 1 - \frac{6\Sigma g}{N^2 - 1},$$

where Σg equals the sum of the gains (a gain is the number by which a specimen's first-column rank exceeds its second-column rank), and N equals the number of specimens in the ranking. The procedure is illustrated by the following application to the data for series *A*—natural weather *vs.* accelerated weather (condition (1))—as given in Tables III and V:

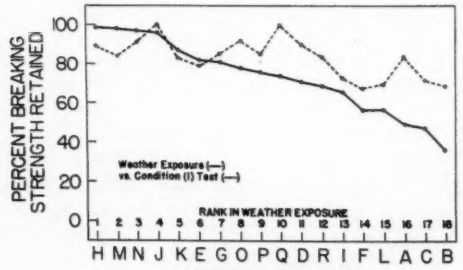
PERCENT BREAKING STRENGTH RETAINED
100
80
60
40
20
0
Weather Exposure (—)
vs. Condition (1) Test (—)
RANK IN WEATHER EXPOSURE
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18
H M N J K E G O P Q D R I F L A C B
SERIES A SAMPLES

FIG. 1. *Effects of natural and accelerated weathering (condition (1)) on breaking strength of finished duck samples. (Series A.)*

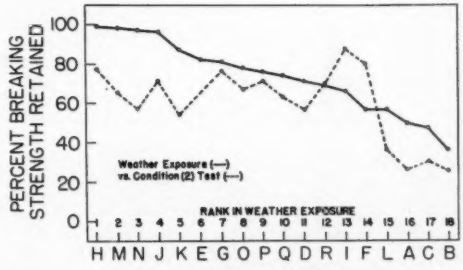
PERCENT BREAKING STRENGTH RETAINED
100
80
60
40
20
0
Weather Exposure (—)
vs. Condition (2) Test (—)
RANK IN WEATHER EXPOSURE
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18
H M N J K E G O P Q D R I F L A C B
SERIES A SAMPLES

FIG. 2. *Effects of natural and accelerated weathering (condition (2)) on breaking strength of finished duck samples. (Series A.)*

Sample designation	Rank by weather exposure	Rank by condition (1) test	Gains
H	1	6	—
M	2	10	—
N	3	4	—
J	4	1.5	2.5
K	5	12	—
E	6	13	—
G	7	7.5	—
O	8	3	5
P	9	7.5	1.5
Q	10	1.5	8.5
D	11	5	6
R	12	10	2
I	13	14	—
F	14.5	18	—
L	14.5	16	—
A	16	10	6
C	17	15	2
B	18	17	1
			$\Sigma g = 34.5$

Fractional ratings occur when specimens tie for the same rank. Specimens F and L in the first column were tied for fourteenth place; the difference was divided and each specimen was ranked 14.5.

Upon substituting the summation of the gains and the number of specimens in Spearman's formula:

$$R = 1 - \frac{6 \times 34.5}{(18)^2 - 1} = 1 - \frac{207}{323} = 0.359.$$

Spearman considers that a coefficient of 0.50 or over indicates a high degree of correlation, while one of 0.20 or less indicates a low degree of correlation. The probable error of any computed coefficient is determined from the formula $\frac{0.43}{\sqrt{N}}$. In this case the probable error is equal to $\frac{0.43}{\sqrt{18}} = 0.10$. To be significant, the value of R must be at least twice as great as its probable error, because otherwise the apparent correlation may be mere coincidence. Spearman deduced that when R is equal to twice the probable error the correlation shown has 1 chance in 6 of being mere coincidence. When R equals 3 times the probable error, the chance of coincidence is 1 in 23; and when the factor is 5, this chance is reduced to 1 in 1,000.

The Spearman coefficients and probable errors calculated for all conditions of accelerated testing *vs.* 12 mo. of weather exposure were:

Series *A*, conditions (1), (2), and (3): Coefficients —0.359, 0.333, 0.304; Errors—0.10, 0.10, 0.10.

Series *B*, condition (2): Coefficient—0.59; Error —0.091.

It is thus evident that even by a rather liberal statistical interpretation of test data no very significant degree of correlation was obtained for the exposures of the series *A* samples, although agreement for the series *B* samples was decidedly better.

Practical information about the value of the accelerated tests was afforded by an even less rigorous method of comparison. This method consists of classifying the samples, on the basis of their performance in natural weather, into groups of good, intermediate, and poor resistance, and calculating percent agreements between like groups when replicate samples are similarly classified from the accelerated tests. This procedure discloses specimens placed in the same group by two different tests, and, considering the inherent variability of the

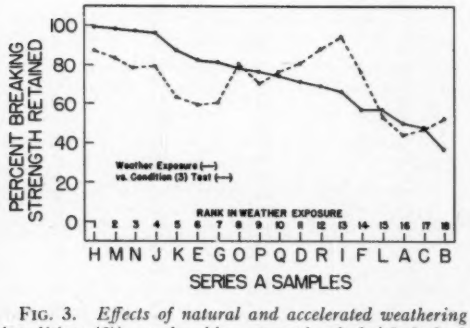
PERCENT BREAKING STRENGTH RETAINED
100
80
60
40
20
0
Weather Exposure (—)
vs. Condition (3) Test (---)
RANK IN WEATHER EXPOSURE
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18
H M N J K E G O P Q D R I F L A C B
SERIES A SAMPLES

FIG. 3. *Effects of natural and accelerated weathering (condition (3)) on breaking strength of finished duck samples. (Series A.)*

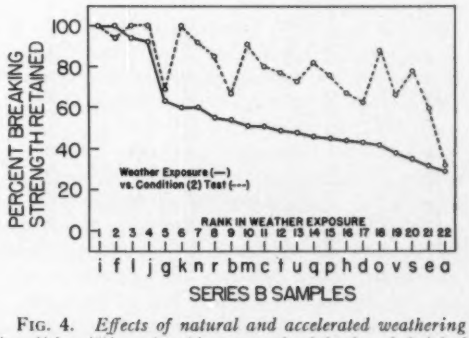
PERCENT BREAKING STRENGTH RETAINED
100
80
60
40
20
0
Weather Exposure (—)
vs. Condition (2) Test (---)
RANK IN WEATHER EXPOSURE
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22
i f l j g k n r b m c t u q p h d o v s e a
SERIES B SAMPLES

FIG. 4. *Effects of natural and accelerated weathering (condition (2)) on breaking strength of dyed and finished duck samples. (Series B.)*

natural weather exposures which must serve as standards of reference, it is probably as informative as any that can be devised. It suffers, however, from the disadvantage that such group classification is more or less arbitrary and may often be open to question.

In Table V the test data are arranged for convenience in making group comparisons. All samples are listed in order of their decreasing strength retentions for the different tests, and the percent strength-retention values are given for the controlling natural weather exposures. In series *A* fairly well-defined intervals in these values serve to indicate natural points of group division between specimens 4 and 5, and again between specimens 13 and 14. In series *B* the upper-division point between specimens 4 and 5 is even more clearly indicated; but for the lower part of the list, where the decrease in values is much more gradual, no point of obvious separation between the intermediate and lowest groups is apparent. Here the division line was placed between specimens 15 and 16. An alternative and even more arbitrary method is to divide the lists into thirds or some other convenient fraction.

The natural and accelerated test results were compared for group agreement after being separated at the apparently logical dividing points as indicated above, and again after being divided as nearly as possible into thirds. By both methods of division the average group agreements between the natural and accelerated weathering tests were found to range from 60% to 65% for series *A*, and to be approximately 75% for series *B*.

Although it could be said that some degree of positive correlation exists between the results of the natural and accelerated weathering tests, the many discrepancies that appeared in the performance of the finished samples made it clear that for practical evaluation purposes, little real dependence can as yet be placed on these artificial weathering techniques. In the series *B* tests, for example, although the untreated controls were degraded about equally and the first 5 ranking samples were in good agreement, all the remaining samples showed considerably more resistance in the accelerated than in the natural weather test. Many other examples of erratic performance were scattered throughout the series *A* results.

Conclusions

Two series of samples of various types of weather-protective finishes applied to a common cotton

TABLE V. RANKINGS OF SAMPLES IN DIFFERENT TESTS

Series *A*					Series *B*		
Rank	Weather (%BSR)†	Condition (1)	Condition (2)	Condition (3)	Rank	Weather (%BSR)†	Condition (2)
1	H 99	J	I	I	1	i 100	i
2	M 98	Q	F	R	2	f 100	l
3	N 97	O	H	H	3	l 94	j
4	J 96	N	G	M	4	j 92	k
5	K 87	D	J	D	5	g 63	f
6	E 82	H	P	O	6	k 60	n
7	G 81	G	R	J	7	n 60	m
8	O 78	P	O	N	8	r 55	o
9	P 76	A	M	Q	9	b 54	r
10	Q 74	M	Q	F	10	m 51	q
11	D 71	R	D	P	11	c 51	c
12	R 69	K	N	K	12	t 49	s
13	I 66	E	K	G	13	u 48	t
14	F 57	I	L	E	14	q 46	p
15	L 57	C	C	L	15	p 45	u
16	A 50	L	A	B	16	h 44	g
17	C 48	B	B	C	17	d 43	b
18	B 37	F	–*	A	18	o 42	h
					19	v 38	v
					20	s 35	d
					21	e 32	e
					22	a 29	a

* Sample E omitted in this test.
† % Breaking strength retention.

fabric were exposed to accelerated weathering tests under conditions which were varied in attempts to obtain results most closely approximating those of actual weather. Statistical interpretation of the data indicated a positive correlation between the two types of tests. However, no constant relationship was found between test results of accelerated weathering and natural weathering by which it is safe to forecast the behavior of such cotton textile materials in outdoor service conditions. Even the generalization that the accelerated methods will discriminate between the very good and very poor test specimens appeared to be unreliable when it was found that some specimens were rated high by one test and relatively low by the other.

It is not evident at the present stage of development of accelerated exposure techniques that the use of accelerated weathering tests can replace actual outdoor weathering for the dependable evaluation of weather-protective treatments.

Literature Cited

1. A.A.T.C.C., *Am. Dyestuff Reptr.* **36**, 705 (1947).
2. Appel, W. D., and Jessup, D. A., *J. Research Natl. Bur. Standards* **15**, 601 (1935).
3. Chapman, E. N., Thesis, Pennsylvania State College, 1941.
4. Clibbens, D. A., and Ridge, B. P., *J. Text. Inst.* **19**, T389 (1928).
5. Lyle, D. S., *Am. Dyestuff Reptr.* **36**, 623 (1947).
6. Lyle, D. S., Wachter, A. R., Rice, C. W., Mack, P. B., and Bonnet, F., *Am. Dyestuff Reptr.* **37**, 251 (1948).
7. Spearman, C., *British J. Psychology* **2**, 89 (1906).
8. Young, H. L., *Am. Dyestuff Reptr.* **32**, 500 (1943).

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Book Reviews

The Examination of Damage in Wool. Mededeling van het Vezelinstituut T.N.O. No. 97. Parts I and II (Vol. I) and Part III (Vol. II) with Supplement. A. D. J. Meeuse, H. A. J. Hietink, and J. Gorter. (In English.) Delft, Netherlands, Vezelinstituut T.N.O., 1949. 145 pages. Price, $2.70 (Vol. I); $2.70 (Vol. II with Supplement). (Available through Stechert-Hafner, Inc., New York.)

(Reviewed by Harris M. Burte, Textile Research Institute, Princeton, N. J.)

In the first two parts of this work, the authors literally sit back and take stock of the subject. Part I contains an interesting and very readable discussion of the problems involved in detecting damage in wool and in differentiating between "damaged" and "abnormal" wool. The following definition is proposed: "Wool is damaged if the amount of damage is so much higher than the usual percentage for that particular type of wool that the serviceability is impaired or undesired effects are encountered either during later stages of the manufacturing process or during the actual use of the finished goods." A survey is presented of possible causes of damage to wool together with the types of damage to be expected. Types of damage are classified under three main headings: mechanical damage; chemical damage; and combination of mechanical and chemical damage.

Part II contains an extensive literature survey in which items are classified according to method of

test. A comprehensive literature survey classified in this manner is an invaluable tool for those who wish to apply existing knowledge to practical problems, and it also serves to indicate along which lines further research should proceed. It should be of use to all who are interested in the examination of damage in wool. Unfortunately, there are several evidences of insufficient proofreading—Table VII–2, for example, gives references to Hall (1939) and Krais (1933), but there are no corresponding references in the bibliography.

The qualitative microscopic methods that are being used at the Vezelinstituut for estimating damage in wool are presented in Part III. Detailed instructions are supplemented by several very illuminating case histories. Without detracting from the quality of the work, it is hoped that future publications will present more information on the important practical problems of sampling and experimental variance.

It is the reviewer's opinion that this is a very timely monograph, and should be a useful addition to the bookshelves of all those concerned with the science of fibers.

Developments in the Cotton, Rayon and Silk Industries in Germany, 1939–1945. F. Charnley, R. G. Fargher, D. W. Hill, and L. H. C. Tippett. New York, British Information Services, 1949. 178 pages; illustrated. Price, $0.75.

In this report, which has just become available for distribution in the U.S., an attempt has been made to assess critically the contributions of the Germans to technical advances in the last decade, the German achievements being placed in their proper perspective in relation to those of the British textile industry. Compiled and condensed in this report is much of the more important information that has appeared from time to time in the B.I.O.S. Final Reports of investigations of German industry after World War II. Subjects covered include fiber production, mechanical and chemical processing, and test methods. A listing of trade names and compositions of German textile auxiliary products is included, and also a listing of the B.I.O.S. Final Reports which are considered relevant and which are available. The authors are the heads of the spinning department and the chemical and mechanical processing divisions, and the Deputy Director of the British Cotton Industry Research Association.

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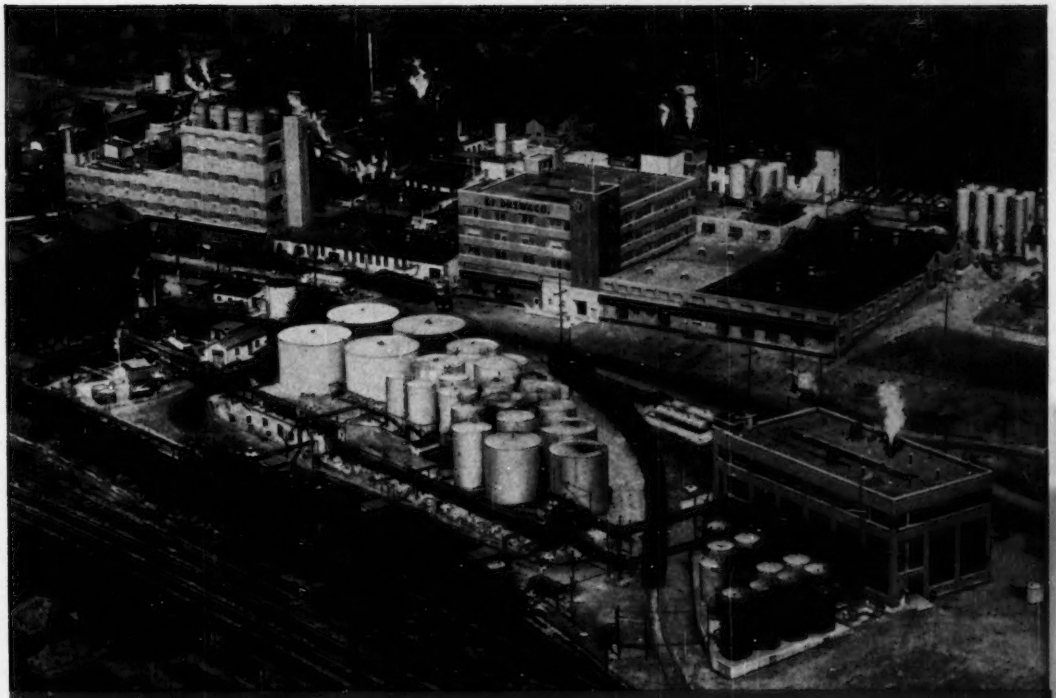

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